SEDIMENTOLOGY AND ENVIRONMENTAL RECONSTRUCTION OF THE CAVAN LIMESTONE, TAEMAS DISTRICT, N.S.W.

by

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Except where otherwise acknowledged in the text, all observational, experimental and interpretive work summarized in this thesis is solely that of the author.

P. Koluzs

Peter J. Koluzs

to my mother and father

"But they that wait upon the Lord shall
renew their strength;
they shall mount up with wings as eagles,
they shall run, and not be weary;
and they shall walk, and not faint."

(Isaiah XL.31)

I thank Thee, Lord.

ABSTRACT

A part of the Murrumbidgee Group, a Lower Devonian carbonate sequence in the Taemas-Cavan area of N.S.W., is defined and formally named the Cavan Limestone. The occurrence within this formation of ancient soil horizons, algal laminations, burrows and desiccation structures, as well as highly fossiliferous strata, by analogy with Recent carbonate environments, indicates that the Cavan Limestone was deposited in an environment very close to mean sea-level. Twelve carbonate and five terrigenous lithofacies were deposited in three major areas of deposition, which were the supratidal, intertidal and subtidal. The carbonate lithofacies and their environments of deposition are:

Lithofacies	Environment
Skeletal grainstone	Shallow subtidal
Skeletal wackestone and packstone	Shallow subtidal
Skel-algal packstone	Shallow subtidal
Mollusk-gastropod wackestone	Lagoonal
Skeletal micritic wackestone	Lagoonal/Shallow subtidal
Micritic mudstone	Lagoonal
Microspar wackestone	Low intertidal
Pelletal wackestone and packstone	Low intertidal
Terrigenous and pelletal wackestone and packstone	Low intertidal
Algal limestone	Low intertidal
Gastropod wackestone	High intertidal/supratidal
Calcrete	High supratidal

The five terrigenous lithofacies are clay, marl, shale, siltstone and sandstone, and are mostly intertidal.

The vertical distribution of these lithofacies enables the formation to be divided into six members. These display highly extensive lateral variations which are explained by lateral migrations and oversteps of coexisting, laterally adjoining facies. To avoid the construction of a wholly impressionistic model of the original distribution of these, they are studied within a 3-dimensional framework, using a Markov analysis, the rationale being that rock types shown to be closely related from this analysis,probably were originally adjacent or close to each other.

Cavan Limestone deposition took place within a shallow north-east trending basin, about 20 km wide. Differences in sedimentation were related to local differential subsidence and hydrography, superimposed on an overall cyclic pattern of subsidence and emergence. This resulted in cyclicity on a member scale, caused ultimately by climatic and epeirogenic events.

ACKNOWLEDGEMENTS

It is with the utmost sincerity that I thank my Supervisor, Dr K.A.W. Crook, for extremely valuable guidance and sustained encouragement throughout all phases of this work.

I would also like to say thanks to Mr G.E. Reinson and Mr Craig Schmidt for their advice and interest in various parts of this project. Mrs H. Drury typed the thesis and her forebearance is gratefully acknowledged. Thanks are also due to the residents of Mountain Creek Property for their hospitality and kindness while I was in the field.

Finally, and most important of all, I say thanks to my mother and father.

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CHAPTER I

1.1 INTRODUCTION

The Taemas-Cavan area is situated approximately 60 km northwest of Canberra, and for the most part lies on the west bank of the Murrumbidgee River (Fig.1). A thick succession of Lower Devonian sediments known as the Murrumbidgee Group[1] (Pedder, 1967b) is well exposed within the area. Since the early thirties this has been divided into three major lithological units. The lowermost and highest of these are richly fossiliferous limestone sequences, whereas the intervening succession consists of multicoloured shales, red sandstones and siltstones. Until now only the upper limestone sequence has been subdivided.

The aims of this thesis are as follows:

1) To prepare a geological map showing the stratigraphy and structures of the lowermost formation in the Murrumbidgee Group, the Cavan Limestone. (During preliminary studies of the area, the formations immediately below and above the Cavan Limestone, the Fifeshire and Majurgong Formations respectively, were also mapped.)
2) To subdivide this formation if possible, and to define new stratigraphic units.
3) To closely examine the sedimentary petrology of the various rock types and, if possible, to relate these to specific depositional environments.
4) Ultimately to arrive at a comprehensive environmental reconstruction and palaeogeography of the Cavan Limestone, within the context of reconnaissance examination in adjoining areas.

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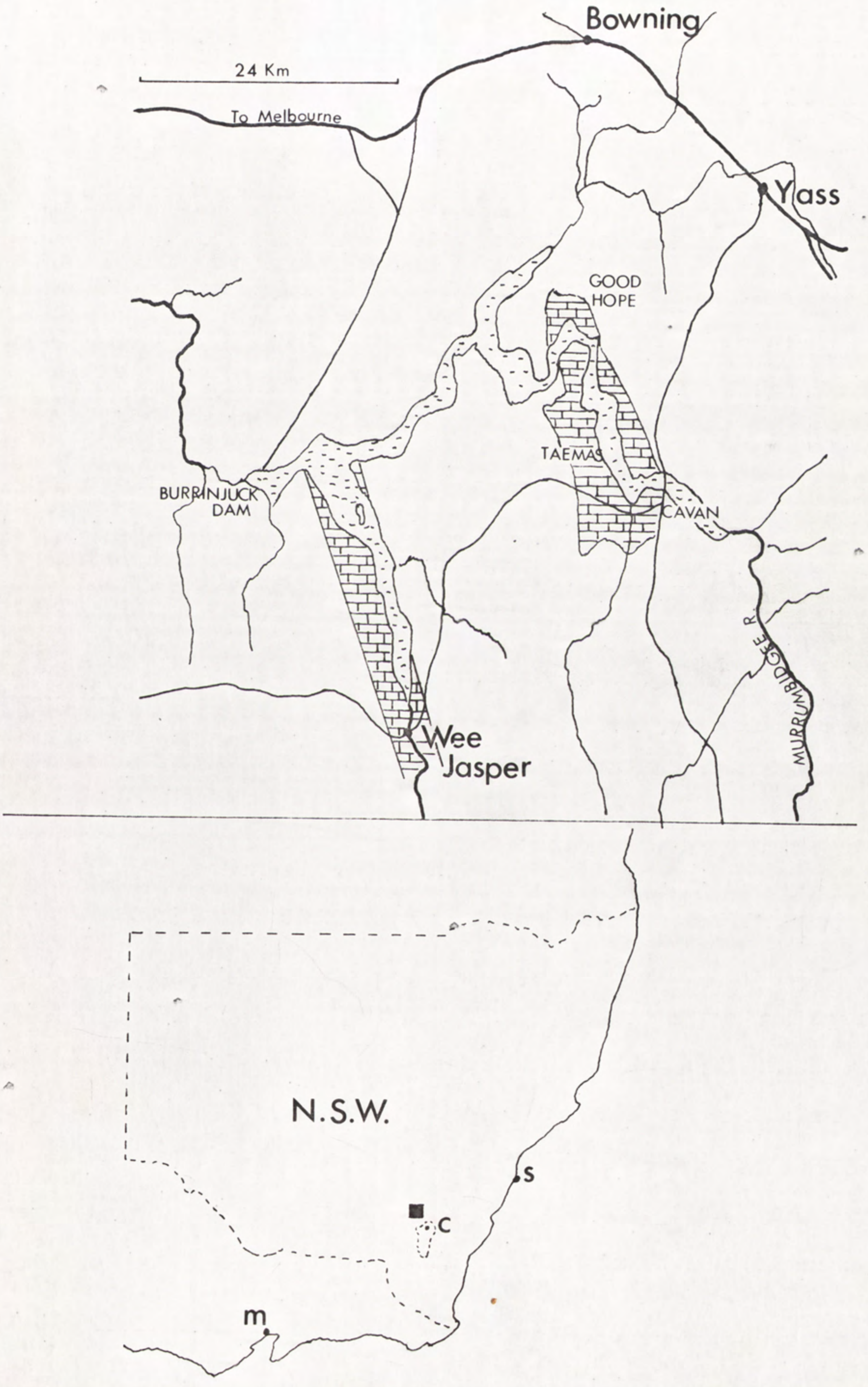
[1]All names are in accordance with the Australian Code of Stratigraphic Nomenclature (1964) except when in quotes.

TEXT—FIG.1. LOCATION OF AREA

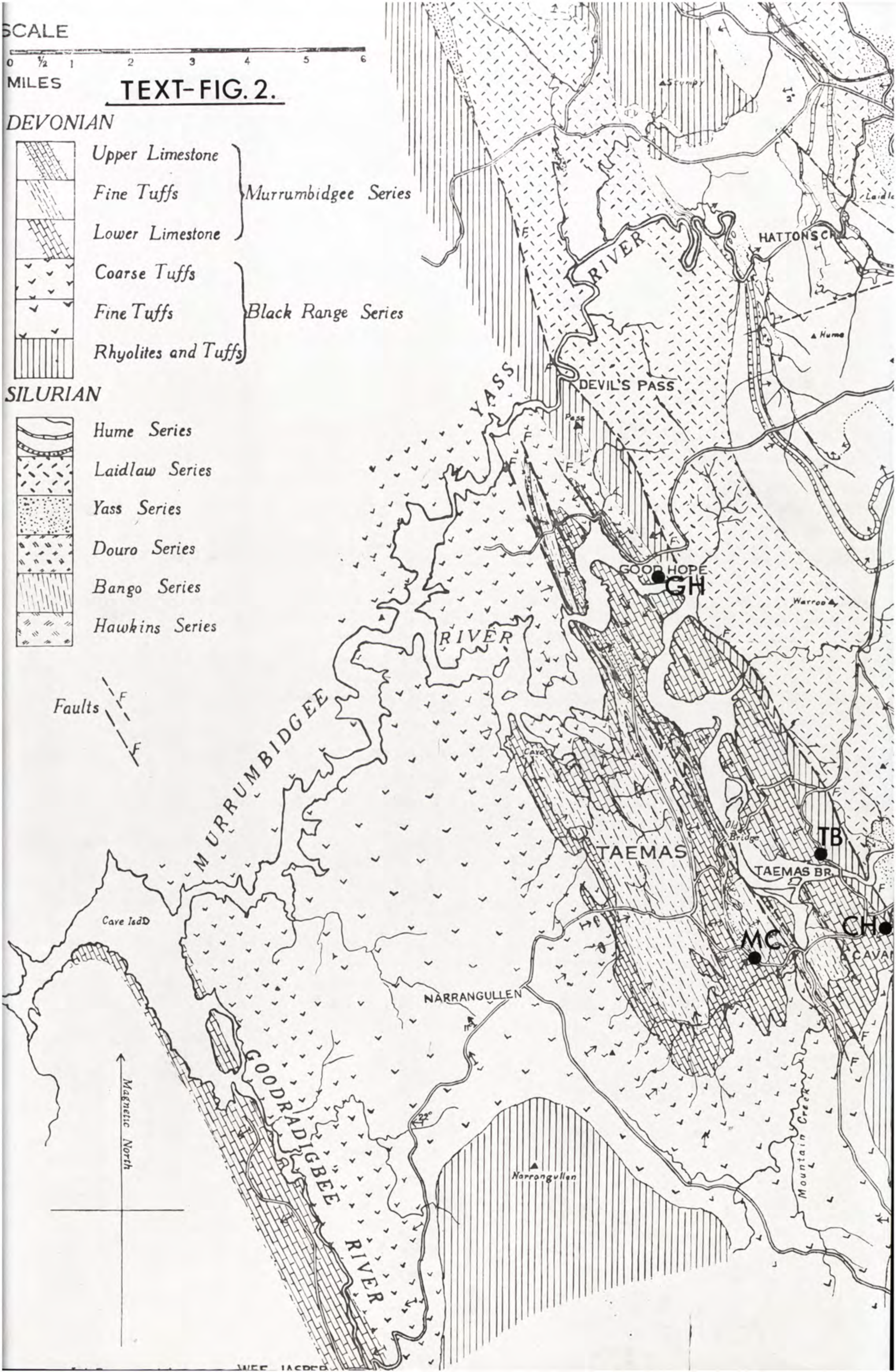


1.2 PREVIOUS INVESTIGATIONS

The Taemas-Cavan area is one of the geologically classic areas of Australia, and has been of interest to geologists for a long time on account of its impressive structures, and its remarkably rich and varied fossil faunas. As far back as 1838 Mitchell realised there were Devonian rocks in the Murrumbidgee Valley, and 12 years later the Rev. W.B. Clarke made the first fossil collections. These were subsequently described by de Koninck (1877, 1898). However, it was not until 1909 with the work of Harper, that any part of the area had been mapped in detail. Three years later Shearsby, who had already contributed a great deal towards the knowledge of the faunas, published a report on the geology of the Yass district (55 km northwest of Canberra). This was accompanied by a map and a section.

In 1932 David divided the sediments into three major units which are now known as the Cavan, Majurgong and Taemas Formations (Pedder, 1967b). Brown (1941) published a paper adding the results of previous investigations to original work, and 14 years later, in 1954, published another paper, together with a geological sketch map of both the Taemas-Cavan area and the Goodradigbee area, about 15 km to the west. This is reproduced in Fig.2 in a slightly modified form. Finally, in 1959 she published another paper, this time specifically of the Taemas-Cavan area. This is the source for most of the later literature dealing with the geology of this area (Philip & Pedder, 1967b; Packham, 1969).

More recently, students of the A.N.U. geology department have mapped in the area (under supervision).


SCALE
0 ½ 1 2 3 4 5 6
MILES
TEXT-FIG. 2.
DEVONIAN
Upper Limestone
Fine Tuffs
Lower Limestone
Murrumbidgee Series
Coarse Tuffs
Fine Tuffs
Rhyolites and Tuffs
Black Range Series
SILURIAN
Hume Series
Laidlaw Series
Yass Series
Douro Series
Bango Series
Hawkins Series
Faults
F
F
Magnetic North
YASS
RIVER
DEVIL'S PASS
HATTONS CR.
Hume
GOOD HOPE
GH
Warroo
MURRUMBIDGEE
RIVER
TAEMAS
Old Bridge
TB
TAEMAS BR.
CH
MC
CAVAN
Cave Isl.D
NARRANGULLEN
Narrangullen
GOODRADIGBEE
RIVER
Mountain Creek
WEE JASPER

1.3 AGE OF THE CAVAN LIMESTONE

Table 1 shows past and current ideas on the age of the Murrumbidgee Group as a whole. Quite clearly a wholly Early Devonian age is favoured.

Conodonts are proving very helpful and of particular significance is the occurrence of Polygnathus linguiformis dehiscens Philip and Pedder. This is probably of Praguian age (Pedder, Jackson & Philip, 1970). In terms of the Rhenish stages, this indicates a late Siegenian to early Emsian age for the Cavan Limestone. However, Klapper (1969) has described a form, Polygnathus lenzi from Nevada and the Yukon Territory, Canada, which is very similar to Polygnathus dehiscens. Since Polygnathus lenzi is considered to be Emsian in age, this suggests that the limestone is no older than Emsian. The situation is complicated further by the fact that Tipheophyllum bartrumi, a common Cavan Limestone coral, overlies upper Siegenian or lower Emsian strata in New Zealand (Boucot et al., 1963). Therefore, although the precise age of the Cavan Limestone may not be known, stratigraphically it may be safely considered to lie close to the Siegenian-Emsian boundary.

1.4 REGIONAL SETTING

The rocks of the Taemas-Cavan area, together with the sediments of the Goodradigbee Valley, form part of the Devonian succession of the Lachlan geosyncline. This structure was initiated in the Cambrian, and contained a number of troughs and highs, one of these highs being the Buchan-Taemas-Molong Platform. This developed in Middle Silurian times as a result of the Quidongan Orogeny. On this platform, during the Early Devonian, the Black Range Group of volcanics and the Murrumbidgee Group of sediments were laid down (Brown, Campbell

TEXT-TABLE I. AGE OF THE MURRUMBIDGEE GROUP

AGE		Hill (1940b) Corals	Philip and Pedder (1964) Conodonts	Philip and Pedder (1967) Conodonts	Sherrard (1967) *Tentaculites*	Pedder, Jackson and Philip (1970) Conodonts	Strusz (1972) Conodonts
Middle Devonian	Eifelian						?
Lower Devonian	Emsian						
	Siegenian & Gedinnian						
REMARKS		The Cavan Limestone is no older than Emsian	The Murrumbidgee Group is wholly L. Devonian, or at youngest may include some lower Emsian strata	Most of the Murrumbidgee Group is Emsian	The Murrumbidgee Group is Lower Devonian	The Murrumbidgee Group is Early Devonian	The Murrumbidgee Group extends from the base of the Emsian to the latest U.Emsian, or possibly slightly into the Eifelian

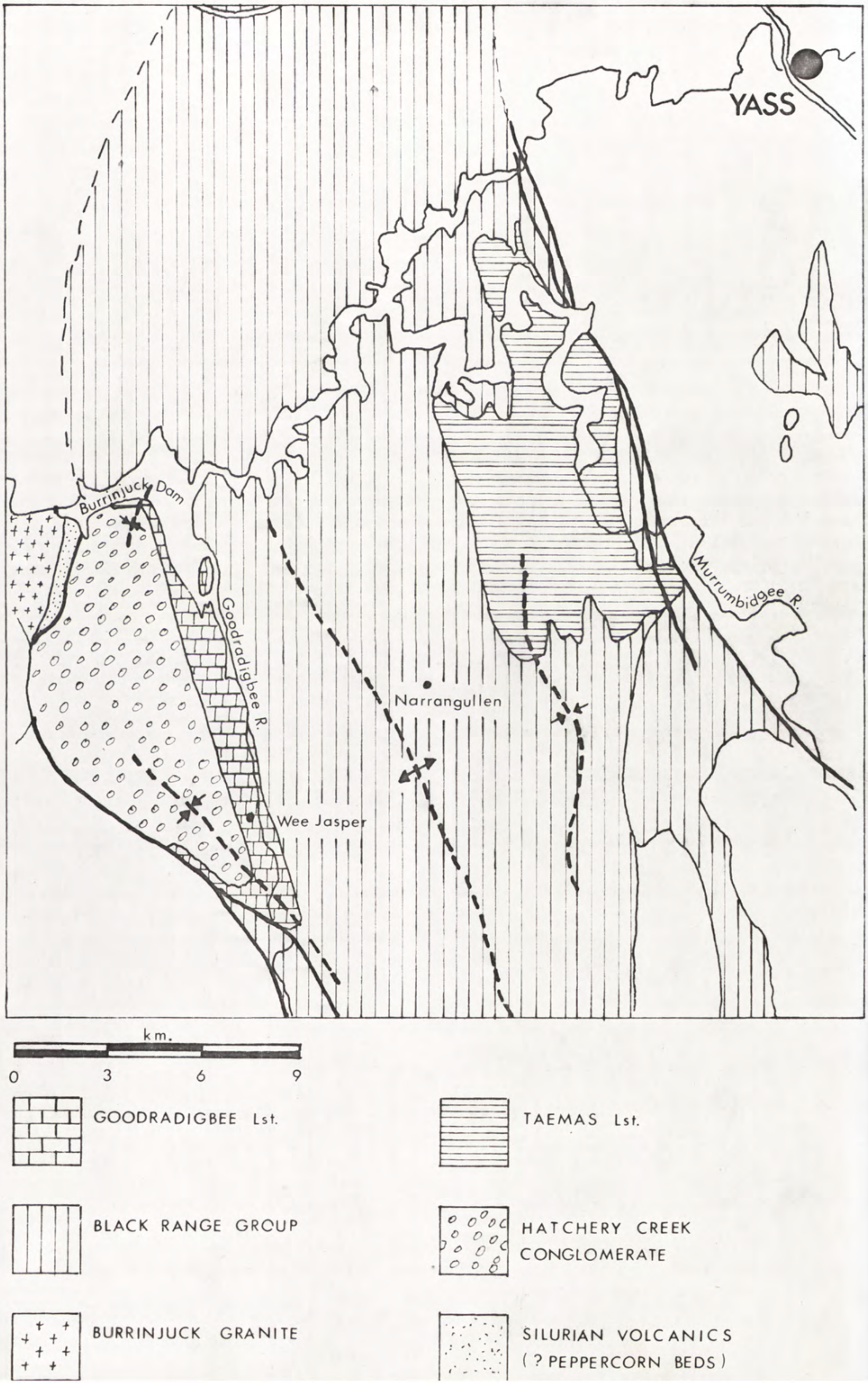
& Crook, 1968). By this time a very great thickness of strata had been deposited, the Silurian and Devonian alone accounting for at least 3,800m in the Yass region. This was a prelude to the ensuing Tabberabberan Orogeny of Middle Devonian times, during which much of the folding now seen in the Taemas-Cavan area probably took place. One likely result is that in the region between the Murrumbidgee and Goodradigbee Rivers, the lavas and tuffs of the Black Range Group now outcrop in a great anticline plunging to the north (Fig.3). The beds of the Murrumbidgee Group have been eroded off this axis, and are confined to the flanks as elongated basins. The western basin is along and to the west of the Goodradigbee River, and is intruded by the Burrinjuck Granite and related igneous bodies. The eastern basin is, in effect, a compound structure, consisting of two synclinoria. The eastern one is much broken by faults, and contains the Taemas-Cavan area (Fig.2).

The similarity in the stratigraphical and faunal successions within the Goodradigbee and Taemas basins is quite striking, and suggests similar conditions of sedimentation and environment over a wide area.

1.5 MAJOR STRUCTURES IN THE TAEMAS-CAVAN AREA

The E-W section (see map) illustrates the essential structure - that of a relatively shallow synclinorium whose eastern flank forms the western limb of an anticline. This synclinorium is in fact a double basin, split into two by an asymmetric anticline, and in overall shape is slightly asymmetric, with a steeper folded western limb. Its axis runs through the vicinity of Glenmaree, and plunges to the

TEXT-FIG. 3. REGIONAL GEOLOGY OF THE TAEMAS-WEE JASPER AREA



N.N.W. The axes of the minor folds also generally run in a N.N.W.-S.S.E. direction. Especially in the Salt Box-Glenmaree-Middle Station area, the folding of these minor structures is simple and open, with about 150m between their crests. Many are strikingly symmetrical with dips in the order of 50°-60°. Outliers of "Spirifer yassensis" Limestone often lie in such structures. In this central area, cleavage is not well developed, but the few measurements taken are in accord with the general cleavage direction. The folds cannot be traced south of the Wee Jasper Road, but this is most probably due to the lack of outcrop. There is no preferred plunge direction.

Folds with the same trend are well developed in the area to the south and east of Little Plain. This region is typified by a basin and dome topograpny, possibly suggesting the presence of cross-folding. However, no clear evidence of such folding was found in any part of the area, except in the region of Salt Box. Here the beds swing sharply to the west, indicating the presence of an anticline with an E-W trend.

Although most of the folding is simple and open, at several localities there are complications due to the extensive drag folding. These structures are variable in size, with amplitudes ranging from 5m - 100m. They are especially well seen close to the boundary of the Fifeshire Formation and the Cavan Limestone, and in regions of very steep dip. They are probably due to the very thin bedded and incompetent nature of the uppermost beds of the Fifeshire Formation.

The major anticline is strongly asymmetric with a very steeply dipping eastern limb, and plunges in a northerly direction. At several localities the beds are almost vertical or overturned. For the most part, the "Spirifer yassensis" Limestone is very steeply dipping throughout the entire length of its outcrop.

Cleavage is especially well developed in the Yellow Limestone Member, where it is often just as conspicuous as the true bedding (Plate IA). General observations only have been made, but it appears that the cleavage planes, which all lie in a direction of 320°-360°, run in the direction of the fold axes, and cut the bedding planes at high angles. Insufficient measurements were taken to determine if there is any fanning of the cleavage.

There is no conspicuous faulting in the area, and this is rather remarkable in view of the extensive folding. Presumably the rocks were plastic enough, or not lithified sufficiently, to resist fracture. This folding probably all took place (only one conspicuous phase) during the Tabberabberan Orogeny at the close of the Middle Devonian.

1.6 METHODOLOGY AND SPECIAL TECHNIQUES

Preliminary sampling was undertaken at 12 localities, and from these, four were finally selected for detailed petrographic study. At these places the succession was carefully measured, and samples, as large as possible, were collected at 30cm - 200 cm intervals and at each obvious lithological change. From these about 800 polished and acid-etched slabs, some up to 35 cm x 25 cm in size, were prepared. These slabs provide a wealth of textural detail, even though the unslabbed samples are often quite homogeneous and uninspiring. Two hundred and fifty thin sections, most of them set in araldite, were also cut, and 40 acetate peels

(Bouma, 1969) were prepared. Some of the thin sections were stained, primarily to determine if any dolomite was present, but none was seen. Three different stains were used:

1) Alizarin red S in 2% hydrochloric acid (Friedman, 1959).
2) Ferric chloride ($FeCl_3$) and ammonium sulphide ($[NH_4]_2S$), (Wolf, 1963b).
3) Titan yellow in 30% sodium hydroxide (Friedman, 1959).

It was found that as a quick "rough and ready" test, the Alizarin stain was best; the $FeCl_3$ stain tended to blacken all the finer grains and to quickly fade away, while the Titan yellow stain took a long time to prepare and necessitated the use of heat for its application.

X-ray analysis of representative samples was also carried out, and indicated that their constituent mineralogy is mostly calcite and quartz with minor amounts of albite, illite and chlorite, and negligible dolomite.

Computer based techniques attempted included cluster analysis and Markov chain analysis. The former technique is a simple form of correlation analysis, a method of searching for relationships in a large symmetrical matrix. It is a straightforward, logical, pair by pair comparison between individuals. The results can be presented in an easily understood 2-dimensional hierarchial diagram in which any breaks between groups can be easily seen. Groups may be picked off at any desired level of similarity or dissimilarity. Parks (1966) provides a good explanation of the rationale of cluster analysis.

A cluster analysis was run on the Cavan Limestone at four localities using such variables as rock type, fossil abundance, type of lamination, and presence or absence of birdseye structure. Unfortunately, in general the results were not as useful as hoped for, but this did not matter, as the Cavan Limestone could be conveniently split up into 17 lithological groups by 'eye'. Nevertheless, upon experimentation it became apparent that with the selection of more meaningful attributes, more useful results might have been obtained.

The other technique, Markov chain analysis (see Chapter 5), investigates the probability of, say, a bed x, following a bed y, and is used to determine if any cyclicity is present within a particular succession. It proved quite useful in the analysis of the Cavan Limestone.

Some work was also carried out using the cathodo-luminescence microscope. Basically this consists of an ordinary petrological microscope fitted with a brass specimen chamber that can be evacuated. A discharge tube is arranged in such a way that a stream of ions and electrons may be directed on to a slide, while keeping the discharge isolated. Under a suitable vacuum, any calcite in the slide luminesces an orange-red colour. However, this is just one of the many minerals which are non-luminescent in the pure state, but which are activated by the presence of divalent manganese. The ferric ion, cobalt ion and nickel ion can quench this luminescence (Sippel, 1965).

It was hoped that the microscope would enable observations of growth structures in pore-filling calcite, and thus provide a reliable method of differentiating such calcite from neomorphic calcite. However, not much time could be spent on this work, and such observations were not forthcoming. Nevertheless, many structures, such as extensively recrystallized fossil fragments, became visible that were entirely absent under ordinary light, and it quickly became apparent that the microscope has great potential in carbonate petrology, in particular in the elucidation of complex diagenetic fabrics.

1.7 TERMINOLOGY

For petrographic descriptions of the samples, the classification and terminology proposed by Dunham (1962) has been adopted, but in a slightly modified form. The innovation is the inclusion in the rock name of a term defining the grain size of the (calcite) matrix, which may vary from micritic to coarse-spar, according to the following table:

crystal size	
100μm	coarse-spar
62.5μm	(medium-)spar
30μm	fine-spar
20μm	coarse-microspar
10μm	(medium-)microspar
4μm	fine-microspar
	micritic

For example, a pelletal packstone with a matrix comprised of calcite grains in the 20μm - 30μm range, may be called a pelletal coarse-microspar packstone.

For crystal textures and fabrics, the terminology employed follows that of Friedman (1965b).

Diagenetic fabrics are described using the terminology shown in Table II. This has been devised using the ideas put forward mainly by Bathurst (1958), Orme and Brown (1963) and Folk (1965).

Finally, Table III shows the classification of bedding employed. It is an extensively modified version of the classifications proposed by Ingram (1954) and McKee and Weir (1953).

TEXT-TABLE 11. TERMINOLOGY OF DIAGENETIC FABRICS

PROCESS	DIAGENETIC FABRIC		
OPEN-SPACE PRECIPITATION	GRANULAR CEMENT		
	DRUSY MOSAIC		
	SYNTAXIAL RIM		
	ENCRUSTING	Lumpy	
		Fibrous	
	FIBROUS		
NEOMORPHISM (Inversion & recrystallization)	NEOMORPHIC GRANULAR CEMENT		
	NEOMORPHIC MOSAIC		
	NEOMORPHIC SYNTAXIAL RIM		
	NEOMORPHIC FIBROUS CALCITE		

TEXT-TABLE III. TERMINOLOGY FOR STRATIFICATION

Thickness	Bedding	Internal structure of stratified unit. May be massive, cross-bedded, contorted etc. or:
	very thick bedded	very thick layered
100 cm		
	thick bedded	thick layered
30 cm		
	medium bedded	medium layered
10 cm		
	thin bedded	thin layered
3 cm		
	very thin bedded	very thin layered
1 cm		
	extremely thin bedded	laminated
0.3 cm		
	ultra thin bedded	thinly laminated

The parting (splitting property) may be flaggy, splintery, slabby or blocky.

CHAPTER 2

DEFINITIONAL STRATIGRAPHY

2.1 INTRODUCTION

Within the Taemas-Cavan region a threefold litho-stratigraphical division of the Devonian is readily apparent. Nowadays these divisions are accorded group status, and have been divided into seven formations. However, adhering strictly to the proposals forwarded in the Fourth Edition of the Australian Code of Stratigraphic Nomenclature (1964), many of the units are informally named or inadequately defined. Current and earlier nomenclatures, together with that used in this thesis, are shown in Table IV, which is adapted from Pedder, Jackson and Philip (1970). The type localities are shown in Fig.2.

The following changes in nomenclature and stratigraphy are adopted:

1) The lowermost formation of the Murrumbidgee Group[1] is formally named the Cavan Limestone.
2) A new formation is defined between the Cavan Limestone and the Sugarloaf Creek Formation, and formally named the Fifeshire Formation.

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[1]For synonomies see Pedder, Jackson and Philip, 1970, p.207.

Text - Table IV. Development of Stratigraphic Nomenclature in the Taemas-Cavan-Wee Jasper area

HARPER, 1909	SÜSSMILCH, 1914		JOPLIN et al, 1953	BROWNE, 1954		BROWNE, 1959			BROWN EX EDGELL 1959	BEST et al, 1964		PEDDER, JACKSON & PHILIP, 1970		IN THIS THESIS, 1972		
purple tuffs	MURRUMBIDGEE BEDS	dk-bl shales with occ. tuffs, 2200m	"Hatchery Creek Conglomerate"		—			(not preserved)	"Hatchery Creek Conglomerate"		"Hatchery Creek Conglomerate"	Hervey ?	Hatchery Creek Formation			—
limestones		Limestones (with interbedded shales & tuffs)	"Goodradigbee Group"	MURRUMBIDGEE SERIES	Upper Limestone	MURRUMBIDGEE SERIES	TAEMAS STAGE	tuffs & shales	"Upper Goodradigbee Limestone"	MURRUMBIDGEE SERIES	Goodradigbee Limestone	MURRUMBIDGEE GROUP	Taemas Limestone	MURRUMBIDGEE GROUP	TAEMAS LIMESTONE	As Browne 1959
								Crinoidal L.S.								
								Warroo L.S.								
								Receptaculites L.S.								
								Bloomfield L.S.								
- - - ? - - -								Currugong L.S.								
tuffs		5600m			Fine tuffs			S. Yassensis L.S.	"Cookmandoon Shales"				Majurgong Formation			S. Yassensis Limestone
- - - ? - - -								Majurgong Stage								Majurgong Formation
limestones					Lower Limestone		CAVAN STAGE	Thin bedded L.S.					CAVAN LIMESTONE		CAVAN LS	U. Foss LS mbr
																Yellow LS mbr
								Bluff L.S.	"Lower Goodradigbee Limestone"							Micritic LS mbr
																Nodular LS mbr
																Bluff LS mbr
								Flaggy L.S.								Flaggy LS mbr
massive purple tuffs		rhyolite lavas & tuffs	"Sugarloaf Creek tuff"	BLACK RANGE SERIES	Coarse tuffs	BLACK RANGE SERIES		Mountain Creek tuffs	"Sugarloaf Creek tuffs"	BLACK RANGE GROUP	"Sugarloaf Creek tuff"	BLACK RANGE GROUP	"Sugarloaf Creek Formation"	BLACK RANGE GROUP		Fifeshire Fm
																"Sugarloaf Creek Formation"
tuffaceous shales		1600 m			fine tuffs						"Kirawin Shale"		"Kirawin Formation"			"Kirawin Formation"
			"Mountain Creek Volcanics"		rhyolites & tuffs			Narrangullen rhyolites	"Mountain Creek Volcanics"		"Mountain Creek Volcanics"		"Narrangullen Formation"			"Narrangullen Formation"

2.2 FIFESHIRE FORMATION

At many localities within the study area the Cavan Limestone passes down into a monotonous sequence of interbedded siltstones, fine sandstones and shales. This lies abruptly, though conformably, on a multicoloured coarse volcanic sandstone unit. The monotonous beds are readily mappable in the field, and for the last few years have been mapped as the lowermost unit in the Cavan Limestone, by students of the A.N.U. However, in lithology and probably genesis, they are very similar to the "Sugarloaf Creek Formation"[2] (Joplin et al., 1953), and, in fact, in this thesis they are regarded as equivalent in age to the uppermost beds of this formation. As a consequence, the Fifeshire Formation, which comprises these beds, is included in the Black Range Group, as opposed to the Cavan Limestone. It follows that the "Sugarloaf Creek Formation" has been reduced in thickness.

Derivation - Fifeshire property, Good Hope (178687 Goulburn), (Log I).

Type Section - Good Hope (182686 Goulburn)

Lithology - Interbedded multicoloured siltstones, fine sandstones and shales. There are variable marly intercalations and occasional tuffaceous units.

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[2]The "Sugarloaf Creek Formation" consists of maroon to purple tuffs, and subordinate arenites, siltstones, shales and rhyolites. The contact is gradational. Earlier synonyms are:
Mountain Creek Tuffs, BROWNE, 1959 (upper part).
Sugarloaf Creek Tuff, BROWN, 1964 (ex Edgell) (upper part)
Sugarloaf Creek Tuff, BEST et al., 1964.
Sugarloaf Creek Formation, PEDDER, JACKSON and PHILIP, 1970, p.211.

Contacts - Passes gradually into the overlying calcareous shales, siltstones and limestone beds of the Cavan Limestone. Its base is arbitrarily placed at the first limestone band. It shows a sharp lower contact with a multicoloured volcanic sandstone unit.

Thickness - 44m - 70m.

Fossils - Nil.

Age - Early Devonian. Probably lies somewhere between late Siegenian to early Emsian, as it directly underlies the Cavan Limestone.

2.3 CAVAN LIMESTONE (Browne, 1959, p.117-118, emend. herein)

Synonomy - Cave(s) Limestone, ETHERIDGE, 1902, p.255, 259, 261; 1920, p.61-62 (= Cavan and Taemas Formations).

Bluff Limestone, HARPER, 1909 (= Bluff, Nodular, and Yellow Limestone Members of the Cavan Limestone).

Bluff Limestone, HILL, 1940b, p.248-249, 256, 266, 272 (= Bluff, Nodular, and Yellow Limestone Members of the Cavan Limestone).

Lower Limestone, BROWNE, 1954.

Cavan Stage, BROWNE, 1959, p.117-118.

Cavan Limestone, PEDDER, JACKSON and PHILIP, 1970, p.210.

Subjective Synonym - Lower Goodradigbee Limestone, BROWN, 1964 (ex Edgell).

The current and widely accepted name for this formation stems solely from Browne's 1959 paper. However, although she adequately defined the formation, strictly speaking, she failed to formally name it. Presumably, later workers (e.g. Pedder, Jackson & Philip, 1970) have failed to realise this, because they still credit Browne with its formal naming even though, possibly quite inadvertently, they themselves have given the formation a formal name.

Derivation - Cavan Homestead, 25 km southwest of Yass along the Yass - Wee Jasper road (186677 Canberra).

Type Section - Clear Hill, on Cavan property (187677 Canberra), (Log II).

Lithology - Flaggy pelletal wackestones and packstones with terrigenous interbeds passing up into massive, skeletal wackestones, overlain by nodular skeletal packstones, biostromal in part. These become micritic upwards and pass into yellow weathering microspar wackestones and calcretes, overlain by poorly exposed skeletal wackestones.

Contacts - The lower boundary is very gradational. The upper contact when exposed is very sharp with sparsely fossiliferous limestone beds, passing abruptly into the brightly coloured shales of the Majurgong Formation. However, in areas of poor exposure the contact seems to be gradational.

Thickness - 88m - 218m.

Fossils - Polygnathus linguiformis dehiscens Philip and Pedder, Tipheophyllum bartrumi, Zelolasma gemmiforme.

Age - Early Devonian. Probably lies somewhere

<u>Age</u> (cont.) - between late Siegenian to early Emsian.

2.4 SUBDIVISION OF THE CAVAN LIMESTONE

This formation was first subdivided by Browne (1959) who recognised the following threefold division[1]:

Thin-bedded Limestone (32m)

Bluff Limestone, with <u>Disphyllum gemmiforme</u>, <u>Tipheophyllum bartrumi</u>, etc. (48m)

Flaggy limestones, shales and quartzite (48m) (base).

However, she did not map these units or name them formally.

In this thesis, six members[2] are recognised. These are:

Mapping Unit III	Upper Fossiliferous Limestone Member Yellow Limestone Member
Mapping Unit II	Micritic Limestone Member Nodular Limestone Member Bluff Limestone Member
Mapping Unit I	Flaggy Limestone Member (base)

The Bluff, Micritic and Upper Fossiliferous Limestone Members often have poor outcrops and as a result are extremely difficult to map. It was therefore found more practical for mapping purposes to split the Cavan Limestone into three subdivisions, made up of the six members as shown above, and to indicate those localities where the three recessive members in question can be best observed or followed for short

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[1] Fifty years earlier, Harper had observed the same general succession (Harper, 1909, p.44).

[2] They are not formally named.

distances (see geological map). These three mapping units correspond to Browne's threefold division.

Flaggy Limestone Member

Derivation - Flaggy aspect of beds.

Type section - Clear Hill, on Cavan property (187677 Canberra), (Log II).

Lithology - Flaggy pelletal wackestones and packstones, interbedded with shales, siltstones and fine sandstones. The sequence often shows flat lying algal laminations and some calcrete.

Contacts - The lower contact is very gradational. Quite often an arbitrary division is necessary when limestone bands are absent in the lowermost beds of the member. The upper contact is well defined with an abrupt change into massive limestone beds.

Thickness - 13m - 80m.

Bluff Limestone Member

Synonomy - Bluff Limestone, HARPER, 1909, p.45 (lower part)

Bluff Limestone, BROWNE, 1959, p.117-118 (lower part)

Derivation - Prominent outcrop.

Type Section - Clear Hill (Log II).

Lithology - Medium- to very thick-bedded skeletal wackestones, occasionally cross-bedded.

Contacts - With a decrease in the thickness of bedding, the member gradually passes into nodular limestone beds above.

Thickness - 5m - 21m.

Nodular Limestone Member

Synonomy - Bluff Limestone, HARPER, 1909, p.45 (upper part).
Bluff Limestone, BROWNE, 1959, p.117-118 (upper part).

Derivation - Nodular aspect of the beds.

Type Section - Mountain Creek Bridge, 27 km southwest of Yass along the Wee Jasper road (183674 Canberra), (Log III). Other excellent sections occur:

1) At Good Hope (182686 Goulburn), (Log I).
2) Near Taemas Bridge, 23 km southwest of Yass along the Wee Jasper road (185676 Canberra), (Log IV).
3) At Clear Hill, (Log II).

Lithology - Nodular, richly fossiliferous packstones, biostromal in parts, and with variable shaly and clayey interbeds.

Contacts - The nodular limestones gradually become finer and pass into the overlying mudstones.

Thickness - 20m - 70m.

Micritic Limestone Member

Synonomy - As for Nodular Limestone Member.

Derivation - Fine grained nature of the beds.

Type Section - As for Nodular Limestone Member.

Lithology - Nodular dark coloured mudstones, occasionally fossiliferous.

Contacts - Sharp upper contact with yellow weathering, often algally laminated limestone bands.

Thickness - 4m - 14m.

Yellow Limestone Member

Synonomy - Yellow Limestone, HARPER, 1909, p.46 (lower part).

Derivation - Yellow aspect of many limestone bands (calcretes). Also general yellow weathering.

Type Section - Good Hope (182686 Goulburn), (Log I). Another excellent section occurs at Clear Hill, (Log II).

Lithology - Yellow weathering microspar wackestones and calcretes, often interbedded with shales. Some algal laminations and common desiccation structures.

Contacts - Passes upwards abruptly into grey weathering skeletal wackestones.

Thickness - 18m - 54m.

Upper Fossiliferous Limestone Member

Synonomy - Yellow Limestone, HARPER, 1909, p.46 (upper part).

Derivation - Fossiliferous nature.

Type Section - Taemas Bridge (185676), (Log IV). A good section can also be seen at Clear Hill, (Log II).

Lithology - Sparsely fossiliferous medium-bedded wackestones.

Contacts - At most localities passes sharply into the overlying shales and siltstones of the Majurgong Formation.

Thickness - 0m - 14m.

CHAPTER III

PETROGRAPHIC ROCK TYPES AND THEIR GENERAL ENVIRONMENT OF DEPOSITION

3.1 INTRODUCTION

The Cavan Formation may be conveniently described in terms of 12 carbonate petrographic rock types. Three of these, calcrete, algal limestone and gastropod wackestone, are defined solely from outcrop appearance. The remaining nine types are based predominantly on thin section studies, both quantitative and qualitative, but may be readily related to the hand specimen. Table V lists the rock types and shows the general parameters used for their definition.

Each rock type is discussed from the point of view of:

1) Outcrop appearance and distribution.
2) Thin section studies. The treatment of diagenetic fabrics is very brief and based largely on the work of Bathurst (1958) and Folk (1965). Only very general conclusions regarding diagenesis are attempted.

Following this, a general depositional environment is inferred for each rock type. It is stressed that this is based exclusively on information given by the particular rock type. In other words, the environment is not considered within the context of adjacent environments, or the environmental setting as a whole. This is done in a later chapter, (Chapter 5), when a general unifying reconstruction is attempted. Environmental energy (Plumley, Risley, Graves & Kaley, 1962) is stressed throughout. The inferred environments for each rock type are shown in Table V.

TEXT-TABLE V. CARBONATE ROCK TYPES OF THE CAVAN LIMESTONE

(^{1}w = wackestone, ^{2}p = packstone)

ROCK TYPE	MAIN PARAMETERS USED*	DISTINGUISHING FEATURES		INFERRED DEPOSITIONAL ENVIRONMENT
		FIELD	THIN SECTION	
Skeletal w^{1} & p^{2}	Fa, P	Nodularity, abundant fauna	Abundant skeletal debris, fine to medium-microspar plasma	Shallow subtidal
Algal Limestone	F	Laminations, desiccation features	Alternation of sediment-rich & algal-rich laminae	Low intertidal
Calcrete	F	Yellow colour	Micritic plasma, scattered quartz grains, pellets	Supratidal
Pelletal w & p	Pe	Very thin bedding	Abundant pellets, fine-microspar plasma	Low intertidal
Skel-Algal p	S	Regular bedding	Abundant skel-algal pellets & grains	Shallow subtidal
Microspar w	-	-	Paucity of allochems, inequigranular plasma	Low intertidal
Terrigenous & Pelletal w & p	P, Ω	Very thin bedding	Abundant quartz & feldspar grains, abundant pellets	Low intertidal
Micritic Mudstone	P	Very fine-grained nature	Micritic plasma, few allochems	Lagoonal
Gastropod w	F	Gastropod intraclasts	Gastropod intraclasts	Supratidal/high intertidal
Mollusk-Gastropod w	Fa	Sparse fauna	Restrictive skeletal debris, micritic to medium-microspar plasma	Lagoonal
Skeletal Grainstone	Fa, P	Coarse-grained nature, abundant fauna	Abundant skeletal debris, spar plasma	Shallow subtidal
Skeletal Micritic w	P, Fa	Very fine-grained nature, some fauna	Micritic plasma, echinoderm debris	Lagoonal/Shallow subtidal

*Fa refers to Fauna, P to Plasma, F to Field, Pe to Pellets, S to Skel-algal, Ω to Quartz & Feldspar

Finally, the terrigenous rocks are very briefly considered.

3.2 CARBONATE PETROGRAPHIC ROCK TYPES

These are considered in decreasing order of volumetric abundance, which is based on the frequency of the particular rock type.

Skeletal Wackestones and Packstones

These rocks occur predominantly either as isolated scattered nodules, bands of isolated nodules (Plate I, 2), or bands of nodules that tend to coalesce, set in a brachiopod-rich clay, marl or shale matrix. The first two habits may be conveniently described as loose nodular, the latter as compact nodular (Plate II, 1). In some cases, however, the nodules are distributed in such a way as to destroy all impression of stratification. The matrix is often greyish yellow (5Y8/4) or yellowish grey (5Y7/2) weathering, silty, sticky and clayey (mostly illite and chlorite) and may contain bands of micrite. In other cases, it consists of black (N1) paper-thin shales which are often wrapped around the nodules. The spacing between these varies from 3mm - 4mm when they are almost touching, to about 20cm.

These nodular limestones grade into semi-nodular limestones that have hummucky top and bottom surfaces, and, in a few cases, pronounced bulbous protuberances on their undersides. These in turn grade into sequences of planar limestone beds of fairly uniform and generally small thickness (15-20cm), alternating with likewise uniform layers of marl. Such sequences, however, are not commonly seen. In fact, in many cases, these nodular beds are only represented in the field either by conspicuously barren patches with a few nodules sticking out of the ground, or, at a distance, by very light grey (N8) clayey-looking areas.

Sedimentary structures, apart from the actual nodularity of the beds, are rare and represented only by a few equivocal cases of sedimentary boudinage and structures produced by interstratal sliding. However, the rocks are richly fossiliferous. Megascopically, brachiopods, echinoids and crinoids dominate the fauna and, for once, laminar stromatoporoids are abundant.

The nodules themselves range in size from about 10cm x 5cm to 60cm x 30cm. Usually they are rounded, but in some parts of the sequence they are definitely rectangular. Their colour varies from medium dark grey (N4) to black. Thin section work shows that their plasma is composed of translucent to very light greyish calcite, and has an average grain size of 12μm. The fabric is xenotopic and notably equigranular. Porphyrotopes are rare and have a maximum size of 35μm.

Microscopically skeletal debris is both abundant and diversified and is composed mainly of echinoid, crinoid, brachiopod, mollusk and gastropod fragments (Plate II, 2). Coral, ostracod, trilobite and bryozoan debris is much less common. Sorting is poor with a size range of 200μm - 10,000μm, and much of the debris is broken and badly worn. None of the fragments shows any apparent lineation.

The echinoid and crinoid fragments show well-defined lamellar twinning, vary from colourless to light brownish and are algally non-corroded. In many cases they display syntaxial rims. When these are absent, marginal calcite grains in the matrix often embay the fragments, giving them a "nibbled" appearance. Pressure solution of the debris is also quite common. Mollusks have micritic envelopes, and like bryozoan and trilobite debris in particular, may show algal encrustations.

Replacement by sooty pyrite and feldspar is often present but selective, and in the case of feldspar, on a very small scale. Pyrite replacement, however, is extremely widespread and absent only from crinoid, echinoid and coral debris. Feldspar replaces ostracod, trilobite and mollusk fragments but, like quartz, generally occurs as detrital grains with an average size of 40μm.

Three diagenetic fabrics are conspicuous. The most common is the granular cement constituting the plasma. This is exceedingly uniform in size and shows grain boundaries that are simple polyhedra, suggesting it is neomorphic in origin.

Drusy mosaic is also very common and occurs within most of the fossil fragments. Generally, it has a precipitative origin, showing many of the features cited by Bathurst (1958) as evidence of drusy growth. Some of the fragments, however, have been replaced neomorphically. This is especially well shown by the gastropod and mollusk debris. In these cases, the organic structure of the original shell, delineated by streaks of brown discoloration, presumably organic matter, or by films of sooty pyrite, continues right through the replacing mosaic (Plate III, 1).

The third type of fabric, syntaxial rim, is not common and is present only on echinoid and crinoid debris. The rim often has a highly irregular outer boundary, and is never in contact with other rims or allochems. In some cases it may be seen to transect the fabric of skeletal fragments. All this indicates it is neomorphic in origin. When the plasma is finer, such rims are extremely scarce suggesting that a very fine plasma may inhibit their growth. However, this need not be the case at all as Evamy and Shearman (1965) for example, have shown most graphically that the crinoid and echinoid overgrowths in the fine grained rocks of the Southern French Jura are not of neomorphic origin, but are an early phase of cement.

General Depositional Environment

These rocks are considered to have formed in a shallow subtidal environment for the following reasons:

1) The relative abundance and diversity of shelly marine invertebrates. The presence of algal oncolites and algal crusts (especially well seen on trilobite and bryozoan debris), suggests well-lit and shallow waters. In addition, the occurrence of the Cystiphyllum biostromes and crinoid and echinoid banks, implies that at times these were warm and well-aerated.

2) Total absence of any features indicating intermittent subaerial exposure.

The probable original deposition of the limestone beds as micrites (subsequently diagenetically altered to medium-microsparites), in itself implies a general lack of strong currents. However, this may also be explained by a dense faunal cover trapping fine materials. Such alternatives may be more profitably examined when the overall depositional environment of the Cavan Limestone is considered (Chapter 5). The distinctive nodularity of the beds is also discussed later.

Algal Limestones

These consist of grey medium- to very thick-bedded, yellow-weathering strata, which have a blocky to slabby parting. Internally they are invariably algally-laminated, and this feature renders this group of rocks most conspicuous in the field. The laminations are essentially flat-lying and have only minor structural modifications, these being represented by a few occurrences of the LLH-S type of stromatolite (Logan, Rezark & Ginsburg, 1964) (Plate III, 2). The laminations are comprised of two morphological types of algal mat, tufted and smooth (Davies, 1970). The latter is by far the more common type and is characterised by planar laminations (Plate IV, 1). Tufted-mat, on the other hand, consists of laminations that have an inverted saucer-like appearance (Plate IV, 2), due to their original configuration on ancient tidal flats as a surface tangle of algal filaments, raised in a series of small twisted tuffs.

The individual laminae range from 0.1cm - 3cm in thickness, and have an average thickness of 0.3cm - 1.5cm. Many of the algal-rich laminae may be recognised by colour banding (Plate V, 1), presumably due to oxidation, whereas the sediment-rich layers are invariably grey in colour. Not uncommonly interlaminated with these rocks are bands 1cm - 7cm thick, of coarse skeletal debris, almost exclusively composed of gastropod or brachiopod fragments. These layers are graded from coarse at the base to fine at the top (Plate V, 2).

Desiccation structures occur throughout but are certainly not abundant. They are represented by the following features:

1) Mud cracks. These are most obvious if they have weathered out on bedding surfaces (Plate VI, 1). Often they define polygonal columns that vary in diameter from 5cm - 15cm. Most probably they have originated from the combined action of algal growth

and desiccation. In sectional views they are more difficult to see and are invariably microscopic in size and filled with calcite.

2) Teepee structures (personal communication Logan; Kayle & Flyod, 1970). These are shrinkage cracks typically localised over domal bedding surfaces, and easily recognisable by their 'wigwam' appearance (Plate VI, 2).

3) Birdseye structure. This consists of vugs that have irregular walls, are calcite-filled and are mostly restricted to one or several laminae (Plate VII, 1). Such characters are not to be expected if these vugs are burrows or 'gas trackways' resulting from bacterial decomposition, as suggested by Cloud (1962). In most cases, they probably originated from internal shrinkage of muds resulting from their dehydration during subaerial exposure. However, many other origins have been postulated (Folk, 1959; Illing, 1959).

4) Broken and disrupted laminae. Such a structure constitutes the lumpy limestone structural type of Matter (1967). In most cases, fragments of the broken laminae are strung out in discrete but discontinuous layers parallel to continuous layers (Plate VII,2). Clearly such layers were once continuous too, for the individual fragments can be easily fitted together. Commonly, in sectional view, mud cracks are closely associated with such layers, or the bedding surfaces show a pattern of shrinkage polygons, indicating that the fragmentation was a desiccation phenomenon. Most probably as the

desiccation increased in severity, so did the fragmentation (Plate VII, 2).

Closely akin to such fragmentation are the intraformational conglomerates. These are rare, however, and never thicker than 10cm. In most cases they probably consist of fragments of polygons torn loose and transported during storm flooding (Shinn, 1964). They are often associated with sedimentational units that display scour and reworking.

The rocks are very sparsely fossiliferous except for scattered gastropod and ostracod debris, and isolated occurrences of normal marine fauna such as disarticulated and broken brachiopod shells (plus the bands of coarse skeletal debris already described). However, isolated vertical burrows up to 1cm long are occasionally present (Plate VIII, 1). They are relatively straight, filled with microspar and pellets, and truncate several bedding planes. They are not abundant enough to cause any significant bioturbation.

In thin section, only in a few instances, which nevertheless are sufficient to permit useful generalizations and inferences, are any recognisable structures, algal or otherwise, other than the megascopically visible laminae, seen (Plate VIII, 2). The dark laminae, which may usefully be thought of as the sediment-rich layers, are comprised of faecal pelletal fine-microspar wackestone, and are often very rich in quartz and feldspar detritus. When relatively thick ($>$.5mm), they sometimes display graded bedding which may be represented either simply as alternations of coarser and finer allochems, or as a grading from larger grains at the base to finer ones at the top. The significance of each graded layer is that it is essentially a single depositional unit related to one energy pulse of relatively short duration, such as a tidal pulse (diurnal or semi-diurnal).

Very rarely, birdseye structure is present and varies from somewhat planar to bubble-like voids, both types being isolated and filled with calcite. The lighter laminae contain very little terrigenous material and fewer faecal pellets. Their plasma is micritic to very fine microspar and, what is of most interest here, occasionally reveals extremely fine and vertically orientated calcite-filled 'threads'. These are almost certainly the calcite-filled moulds of algal filaments,and represent the external shape of the mucilaginous sheath of the filament. As such they reflect the vertical orientation of algal filaments within the body of the lamina. However, they often form a tangled horizontal series of tubules at the top (Plate IX, 1), which invariably have recrystallized to dense cryptocrystalline calcite. The moulds provide the best a priori evidence for the former widespread occurrence of algae throughout these rocks. However, their former presence is also strongly suggested by a few, though conspicuous, small-scale structures in which the sediment-rich laminae are steeply inclined, vertical or even overturned, although it is emphasized that the great majority of the laminae are essentially planar. Such structures are most logically explained in terms of the action of a binding film, such as an algal film. Moreover, the tendency for such films to exaggerate substrate irregularities by the formation of thicker laminae over topographic highs,is indicative of an organic control on deposition. Purely mechanical deposition usually tends to reduce irregularities by filling the depressions (Wolf, 1965a).

General Depositional Environment

These rocks are considered to have formed in an environment that was periodically flooded and exposed, such as the intertidal to supratidal environments. This interpretation is based on the presence of the following features:

1) Algal laminae. In accordance with the work of Ginsburg _et al_., 1954, Ginsburg, 1960 and Logan, Rezak and Ginsburg, 1964, these organo-sedimentary structures are interpreted as having been formed by gelatinous films of filamentous blue-green or green algae living close to mean sea-level. Since the laminae are notably flat-lying a sheltered environment is envisaged, possibly similar in this respect to the Gladstone embayment in Shark Bay, Western Australia (Davies, 1970).

2) Desiccation structures. Although fairly widespread, these are nowhere as abundant as, for example, in the tidal flat deposits of the Ordovician of Western Maryland (Matter, 1967), or in the tidal flat areas of the Persian Gulf (Kendall & Skipwith, 1968, 1969).

   a) Polygonal mudcracks. These invariably form when water-saturated muds become exposed to the air. It should be borne in mind, however, that they have been observed in a tidal channel under several metres of water (Van Straaten, 1954), and that Burst (1965) produced small-scale cracks with polygonal surface patterns subaqueously. Although they may form in various environments such as flood plain, abandoned river channel and tidal flat, lithological data plus their association with certain other environmental indicators, strongly implies that in this case they formed in a tidal flat environment.

   b) Teepee structures. These are interpreted as having formed initially by the upturning of beds along shrinkage cracks caused by subaerial exposure of the initial sediment. The upturned beds would tend to dry out faster than the area between the shrinkage cracks.

c) Birdseye structure. As already commented on, these structures probably originated from internal shrinkage of muds.

3) Vertical and isolated burrows. Similar structures can be seen in the recent tidal-flat sediments of Barnstable Harbour and Buzzard's Bay, Massachusetts (Rhoades, 1967). Here organisms living in the intertidal to supratidal regions are subjected to drastically fluctuating conditions of temperature, salinity, food supply and other ecological factors, and respond by making vertical burrows as a means of stabilizing the immediate physical environment. The absence of horizontal burrows in the algal rocks of the Cavan Limestone is most significant, as Rhoades' work shows that such burrows are best developed in offshore level bottoms.

The lack of a marine biota is consistent with an intertidal to supratidal interpretation. In fact the isolated occurrences of normal marine fauna probably represent debris thrown on to the flats during abnormally high tides. In this connection, it is significant that present-day flats often display a surface littered with marine skeletal debris after storms or unusually high tides. Cyclonic conditions could also deposit the bands of coarse graded skeletal debris seen throughout these algal rocks, and also provide the material for conglomeratic units (Ball, Schin & Stockman, 1967). Scour surfaces indicate there was active erosion by flood waters.

Specific Environment

The morphology of the algal mats is environmentally most significant. In the Gladstone embayment, Shark Bay, tufted mats are limited to areas of frequent wetting and low sediment influx. This observation together with the work of Hagen and Logan (1970, unpublished thesis) strongly suggests that these mats are confined to depressions in the middle and upper intertidal areas. Smooth mats, on the other hand, are found in two areas, the outer intertidal zone and on the floor of large channels. Since the algal rocks of the Cavan Limestone consist almost exclusively of smooth mats and show no major tidal channels, it is inferred that they formed for the most part on the outer intertidal area of a sheltered ancient tidal flat. This fits in nicely with their relative lack of desiccation features because of less prolonged exposure. The only demonstrably supratidal units within the algal rocks are those beds exhibiting birdseye structure ("such features are a diagnostic feature in all fine-grained supratidal sediments ..." Schin *et al.*, 1969, p.1210). Such units, however, are very minor.

Calcrete

Until now calcrete has not been described from the area. As a result, in this thesis this rock type is treated in a fair amount of detail, especially as regards the problem in nomenclature and its differentiation from algal rocks.

During the last few years a great confusion in terminology has arisen regarding calcareous deposits (such as calcretes) formed at or near the ground surface, in many of the more tropical parts of the world. In different regions these deposits have been referred to by different names (Heath, 1966). Perhaps the best known is caliche, a name first applied by Blake (1901) to the soil carbonates in Southern Arizona. However, in Chile and Bolivia, it has long been applied to soils rich in sodium nitrate.

In Australia and parts of the United States, deposits of soil carbonates have frequently been called travertine and tufa (Crocker, 1946; Fairbridge & Teichert, 1953), whilst in India, geologists writing in English frequently use the word kunkur when referring to carbonate nodules in the soil developed on the Indo-Gangetic alluvium (Wadia, 1953; Krishnam, 1960). This spelling has been somewhat modified to kankur by geologists working on Quaternary soil carbonates that blanket much of South Australia (Horwitz, 1958; Crawford, 1965).

Other terms in use include croute and calcrete. The former is widely used in North West Africa, particularly in Algeria (Durand, 1951; Dalloni, 1951). The latter, first coined by Lamplugh (1902) to name limestone debris cemented by secondary calcite, enjoys most popularity in South Africa (Du Toit, 1954). Lately, however, its usage is becoming more common in Australia due to the work of Logan and Davies in Shark Bay. They refer to carbonates formed by pedogenic processes as calcretes, and in this thesis, it is suggested that any carbonates formed by such processes be called calcretes.

The calcretes in the study area consist of medium-bedded strata that have a blocky parting and invariably are bright yellow in colour. Two types may be distinguished. One is internally structureless and may be called massive calcrete, the other displays planar or wavy laminations and may be termed laminar calcrete. Both varieties are confined to the Flaggy Limestone and Yellow Limestone Members of the Cavan Limestone, and form units with a maximum thickness of about lm. Massive calcrete is particularly conspicuous when it occurs as regularly spaced bands separated by recessive shaly or clayey units as at Clear Hill or at Good Hope (Plate IX, 2). In thin section it is characterised by a dense, yellowish micritic to very fine-microspar plasma. This varies in size from 2μm - 10μm, has few porphyrotopes, and is hypidiotopic and equigranular. The only conspicuous allochems are poorly sorted, scattered and extremely angular quartz and feldspar grains which vary in size from 15μm - 100μm. Very occasionally, a few faecal pellets or the odd heavily recrystallized skeletal fragment may be present. Birdseye structure is quite common and occurs as elongated sub-parallel, isolated and calcite-filled voids. The only conspicuous diagenetic fabric is the drusy mosaic within the birdseye voids.

Of more interest in thin section is the laminar variety. Here, in contrast to algal laminations, the laminae are defined predominantly by differential staining (Plate X, 1). They consist of an abundance of pellets with an average size of 70μm. These are demonstrably different from skel-algal pellets and may be differentiated from typical faecal pellets by their grey coloration, poorer sorting, and dark brown margin. Scattered throughout are quartz grains with an average size of 50μm. These are angular to subrounded and in many cases are being replaced by calcite. Hematite euhedra, mica laths and very heavily recrystallized fossil fragments occur in negligible amounts. The sparse matrix consists of dense, yellow cryptocrystalline calcite.

In areas of rock that are sparsely laminated, pellets are much less prevalent and the rock is comprised mainly of dense yellow equigranular calcite with a size range of 2 m - 8 m. Quartz grains are also reduced in abundance but often show calcite replacement (Plate X, 2). Scattered throughout are thin discontinuous bands and streaks, both of organic and iron-rich material.

Massive calcrete is quite unique and readily recognisable in the field. However, were it not for the conspicuous yellow colour of laminar calcrete, its field differentiation from some of the algal rocks would be very difficult. Thus, besides displaying banding that appears similar to S-mat laminations, not uncommonly it develops laminae that simulate LLH S-mat type laminations (Plate XI, 1). In addition, broken and disrupted laminae, and birdseye structure occasionally occur (Plate XI, 2). Nevertheless, field and thin-section evidence indicate certain differences between laminar calcretes and algal rocks.[1] Some of these have already been pointed out, but for the sake of completeness are listed again. It is emphasized, however, that there are exceptions to all the criteria listed and that, as pointed out by Multer and Hoppmeister (1968, p.191), "a single stromatolitic zone in ancient rocks may contain both subaerially formed laminae (calcrete rock type), and similar-appearing laminae of marine algal origin (algal rock type).superimposed upon one another". The same point has been strongly emphasized by Logan (personal communication). In the study area, some of the differences are:

1) Laminar calcretes are yellow through and through, whereas the algal rocks are generally grey, although they often weather yellow.
2) The bands in laminar calcrete are due for the most part to differential staining. In contrast, those in the algal limestones are defined mainly by textural changes.

[1]Naturally this refers only to the area studied.

3) No traces of algae, including algal moulds, are apparent in the laminar calcretes.

4) The pellets in the laminar calcretes are different from those in the algal rocks.

5) Quartz grains in the laminar calcretes often display replacement by calcite.

6) The fossil roots of plants occasionally occur in calcretes, but none has been found in the algal limestones.

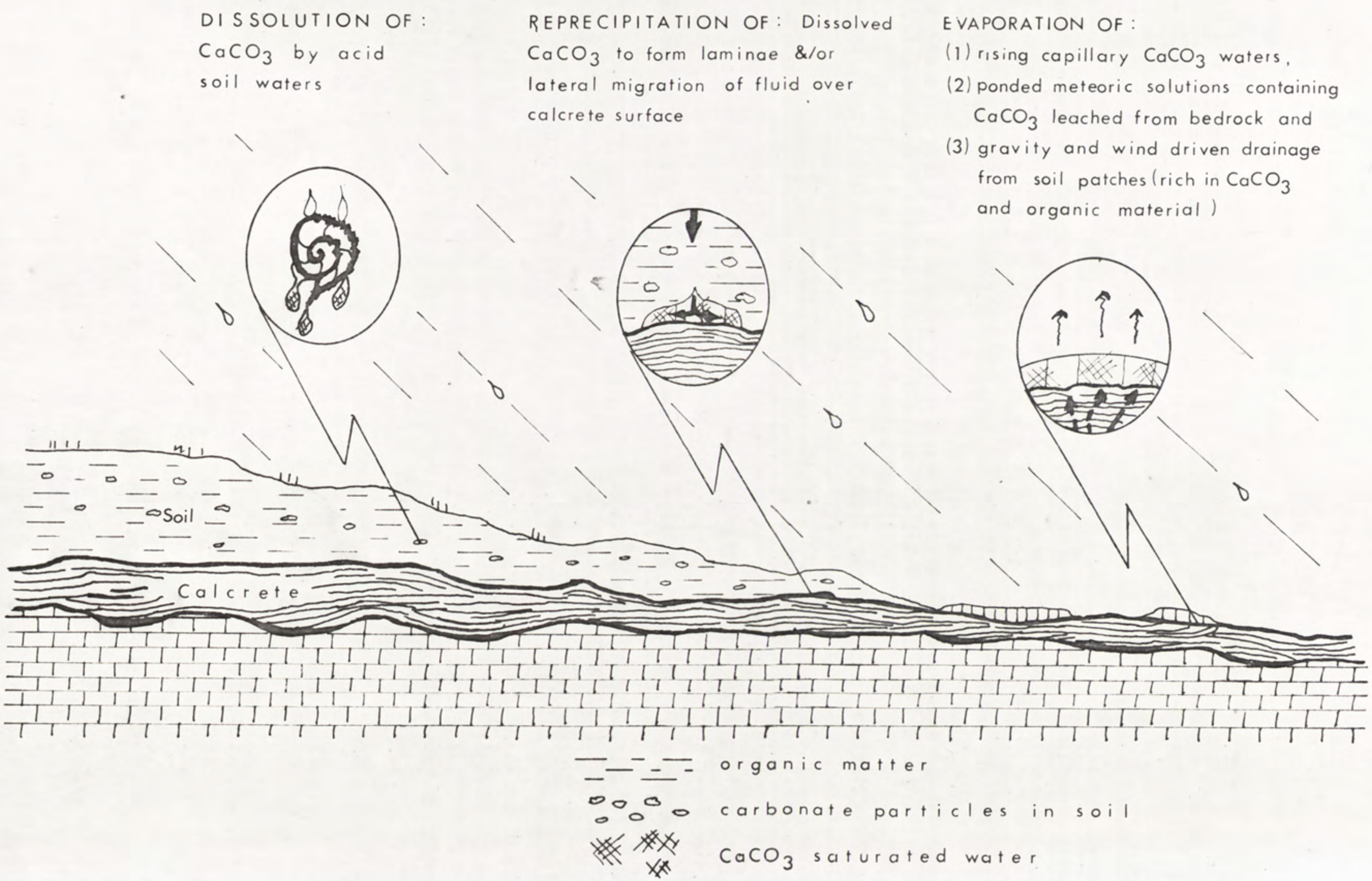
Depositional Environment

These rocks are considered to have formed on exposed or soil-covered limestone surfaces adjacent to the supratidal zone. This assumption is mainly based on analogous occurrences of very similar rocks in Western Australia (Logan, personal communication) and in the Florida Keys area (laminated crusts of Multer & Hoffmeister, 1968). During the wet season there is saturation of the subsoil and downward leaching. On drying, precipitation of calcium carbonate occurs. The mechanism of formation of calcretes in the soil is thus one of solution-precipitation. This explanation fits in well with the one characteristic common to all areas where calcrete is forming today, namely that of a deficient rainfall (about 20 inches), with the rains followed by seasonal drought (Moseley, 1965).

Fig. 4, modified somewhat from Multer and Hoffmeister (1968, p.187), shows very schematically some of the more specific mechanisms responsible for calcrete formation. Laminar calcrete forms later than the massive variety due to a plugging (reduction in permeability) of the calcrete profile. However, complete classic calcrete sequences (Reeves Jr, 1970) were not seen, and so this feature cannot be commented on.

TEXT-FIG. 4.

VARIOUS MECHANISMS FOR THE FORMATION OF CALCRETE



It should be realized that in general subaerial processes operating on land areas adjacent to the high tide mark are many and complex. In particular the pH varies greatly and, as a result, localised solution and reprecipitation could lead to isolated patches of calcrete, depending on whether local precipitation is equal or in excess of solution.

Faecal Pelletal Wackestones and Packstones

These consist almost invariably of grey, extremely thin-bedded to medium-bedded, internally structureless, strata that have a splintery to blocky parting. Mottled weathering in brownish grey (10YR6/1) and yellow orange (7.5YR7/8) is a common feature. Very rarely the beds display laminations. These are approximately 2mm thick (thinly laminated), and are due to alternations in the amount of quartz.

In thin section the rock type is characterised by an abundance of faecal pellets, occurring, for the most part, in a fine-microspar plasma[1] (Plate XII, 1). Quartz and feldspar grains, together with skeletal debris, are the minor components.

The pellets are composed of homogeneous and structureless cryptocrystalline calcite, are well sorted, dark in colour and round, ovoid or ellipsoidal in shape. They have a maximum size of about 80 m and an average size of approximately 45μm. This small average size is their most distinctive characteristic, and is the only one that can be used with any degree of reliability to distinguish them from skel-algal pellets. (See p.38.) When the packing density is low, the individual pellets commonly tend to lose their identity and a clotted texture is seen.

The plasma is almost invariably comprised of fine-grained microspar, exhibiting a translucent, equigranular and xenotopic fabric. Porphyrotopes are rare and have a maximum

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[1] Equals matrix

size of 30μm. Occasionally the plasma is composed of dense, very fine-grained microspar (5μm - 6μm). In these cases appreciable skeletal debris is present. In general, however, such debris is very minor and composed principally of ostracod shells. Other faunal types present include mollusks, gastropods, brachiopods and cricoconarids. Sorting is poor, with a size range from about 300μm to 3500μm. Their mode of preservation is variable, both articulated and disarticulated valves being the case, but most of the debris is only slightly worn. In a few instances, a faint alignment of ostracod valves is apparent.

Quartz and feldspar are common and have a fine average grain size of 50μm. The quartz grains are monocrystalline with straight to undulose extinction, are angular and contain few inclusions. The feldspar grains are also angular, and notably fresh, although a minority show evidence of vacuolization. Twinning and zoning are common. Overgrowths are rare. Both types of grain are predominantly detrital. Near the base of the Cavan Limestone, quartz predominates over feldspar, but the reverse is the case higher in the formation.

Two diagenetic fabrics are conspicuous. The more common is the granular cement comprising the plasma. The other type, drusy mosaic, occurs within skeletal fragments, and invariably shows an increase in crystal size away from the surface on which it has grown. All the fossil fragments are heavily recrystallized.

Depositional Environment

As illustrated by the pelletal mud facies of the Bahamas (Purdy, 1963), pelletal-rich sediments may typify a range of environments, from subtidal through to supratidal. However, in most cases they are most characteristic of intertidal areas (Lucia, 1972, "Recent carbonate intertidal sediments commonly appear to be pellet packstones ..."; Textoris, 1968; Laporte, 1971). This seems the most likely environment for the faecal pelletal rocks of the Cavan Limestone and this interpretation is based on the following observations:

1) Lack of normal marine biota.
2) Lack of desiccation structures, which would be expected in a supratidal environment. In fact, like the algal limestones, these pelletal rocks may well have been deposited on lower intertidal areas, where desiccation processes would be at a minimum. Nevertheless, the presence of fresh feldspar suggests sufficient subaerial exposure to supratidal conditions to restrict its alteration.

The only evidence of current action is given by the occasional faint alignment of skeletal debris. This fits in with Purdy's suggestion (1963) that the formation of many of the faecal pellets in the Bahamas is dependent upon relatively low bottom-current velocities.

<u>Skel-algal Packstones</u>

These rocks occur as grey to black (N4 to N2), thin- to thick-bedded strata, that have a blocky parting (Plate XII, 2). They are notably brittle and give a resonant ring when struck with a hammer. Internally they are structureless except in a few cases when they display laminations. These are on a millimetre scale (thinly laminated), and are defined by alternations in the concentration of quartz and feldspar grains. In most cases they are not visibly fossiliferous.

The beds are particularly common in the Bluff Limestone and Upper Fossiliferous Limestone Members. They form units up to 6m thick, and are often closely associated with skeletal rock types, from which they can usually be differentiated by their seemingly unfossiliferous and dark, brittle nature.

In thin section the diagnostic allochems are algally-corroded fossil fragments (Plate XIII, 1) for which the name skel-algal is proposed. In most cases they occur in a medium-microspar matrix, whilst examples of a coarse-microspar or even a fine-spar matrix are not uncommon. The fabric of this matrix is equigranular, xenotopic and generally translucent, occasionally exhibiting a light grey coloration. Porphyrotopes are not common and have a maximum size of 100μm. Only in rare instances is the matrix a fine microspar.

There is a complete gradation in the severity of the algal corrosion. Thus whilst many fossil fragments show almost negligible corrosion and are easily identifiable, more intense corrosion may lead to the complete destruction of the skeletal fragment, resulting in a grain composed entirely of homogeneous and structureless cryptocrystalline calcite (Plate XIII, 2). Such allochems may be called skel-algal pellets and seem to be derived almost solely from echinoid or crinoid debris. The first stage results in a loss in the definition of the lamellar twinning of the fossil fragment, concurrent with the development of a turbid light brown coloration. This is followed by more intense corrosion, which may proceed either outwards from the centre or inwards from the margins. In a few instances, mollusk and gastropod debris has also undergone complete algal destruction.

A second mode of formation results from the break-up of the corroded margins of skeletal debris, which may be mollusk, brachiopod, gastropod, echinoid or crinoid. It seems reasonable to suppose that many of the smaller skel-algal pellets formed in such a way, in particular the more diffuse types (see Wolf, 1965a, fig.23, p.146).

It should be apparent that texturally skel-algal pellets are very similar to faecal pellets. However, their much larger average size of 80μm - 110μm, their less regular shape, and their association with a diversified skeletal debris, is usually sufficient evidence to permit discrimination. Admittedly, both types may occur in the same slide, when their differentiation becomes particularly difficult. In fact, with the effects of diagenesis, this may be impossible (see Wolf, 1965a, Table III, p.137).

Non-corroded or only slightly corroded debris often accompanies the skel-algal allochems and consists mostly of echinoid and crinoid fragments. Many of these show excellent lamellar twinning or are colourless. Next in order of abundance are mollusk, gastropod and brachiopod fragments, often displaying thin micritic rims (micritic envelopes of Bathurst, 1966). Ostracod, trilobites, coral, bryozoan (sometimes encrusted by algae), and cricoconarid debris is sparse. Sorting is poor to moderate, with a size range from 350μm to 6000μm. Most of the debris, although often broken or disarticulated, is only slightly worn, and occasionally a faint alignment of shells is apparent, especially in the case of mollusks.

Replacement by pyrite, quartz or feldspar is invariably present but usually only on a negligible scale. Nevertheless, this replacement is apparently quite selective. Thus one habit of pyrite is as a sooty film occurring only on trilobite, brachiopod and ostracod debris, and usually penetrating even the most minute surface pores (Plate XIV, 1). Quartz and feldspar replace brachiopod, mollusk and gastropod debris. Occasionally, such replacement becomes extremely pronounced and, in such cases, feldspar, probably albitic in composition, is by far the dominant pseudomorphic mineral, completely replacing the skeletal debris, except for any micritic rims (Plates XIV, 2 & XV, 1). It is always confined within the fossil outlines, anhedral in shape, generally clear or very light brownish, and free of inclusions. Twinning is absent, but cleavage is often well developed, which is handy for distinguishing the feldspar from quartz. The echinoid and crinoid fragments are conspicuously free from any such replacement.

Quartz and feldspar also occur as detrital grains occasionally concentrated in bands about 150μm thick giving laminations. They have an average size of between 70μm and 80μm, and are very similar to those occurring in the faecal pelletal wackestones and packstones. Some grains of feldspar, however, are demonstrably authigenic (Plate XV, 2).

Other grain types are present only in trace amounts and include algal lumps and opaque minerals. The algal lumps, unlike the faecal and skel-algal pellets, have a grumous texture and are relatively very large, reaching sizes greater than 1000μm. They are always intimately associated with skeletal debris that displays extremely thick algal crusts. Surprisingly, such debris is often crinoidal or echinoidal.

The opaque minerals consist mainly of pyrite which shows four morphological types, the most widespread being the fine films of sooty pyrite already described. The other types are seen as minute spheres occurring in clusters, cubes, and as encrusting masses. Quite often the pyrite is closely associated with quartz and feldspar, which it may even replace.

Two diagenetic fabrics are conspicuous and these are the same as those occurring in the faecal pelletal wackestones and packstones (see p.36).

Depositional Environment

Concentrations of skel-algal grains are very common on the low intertidal areas of carbonate tidal flats (Davies, 1970; Textoris, 1968), and several environmental factors are probably responsible for this. In this environment, cyanophyceon algae may be very abundant, and with slow rates of skeletal carbonate production and burial, algal boring of individual grains could continue for a longer time. However, these skel-algal rocks also contain an appreciable non-corroded, diverse and fully-marine fauna, and so an environment transitional between low intertidal and shallow subtidal is postulated. Since, in all probability, these rocks were originally deposited as micrites (subsequently diagenetically altered to micro-sparites), a reasonably quiet, semi-protected type of environment may be envisaged, similar in this respect to a lagoon. However, in such an environment there would have to be sufficient assimilable organic matter, warm temperatures, maximum sunlight, and frequently renewed waters to sustain the diverse biota. All this suggests minimum restriction to a normal marine environment. In fact it is conceivable that the rocks, like the skeletal wackestones and packstones, may have formed in a higher energy environment with no restriction to circulation, and that a dense floral growth on the sea floor served as an effective barrier in trapping fine sediment (Tyler, 1969). In either case, however, these rocks probably formed some distance landwards of the skeletal rock types, because of the abundance within them of skel-algal grains.

Microspar Wackestones

Composing this group are strata that are light grey (N5.5), sparsely fossiliferous, thin- to thick-bedded and with a blocky or slabby parting. Internally they are structureless. They occur sporadically throughout the entire succession, and are often associated with algal beds. They form units with a maximum thickness of 2 m. Ironically, the most conspicuous characteristic of these rocks on the outcrop is their lack of features.

In thin section they are characterised by a paucity of allochems, and an inequigranular microspar plasma (Plate XVI, 1). This plasma is composed of translucent and hypidiotopic calcite, with a general size range of 8μm to 20μm, although prophyrotopes up to 50μm are common. In most cases the rocks may be classified as medium microsparites.

The grain types usually consist of a mixture of organic fragments, quartz and feldspar, and a few skel-algal pellets. The skeletal debris is restrictive in nature, being composed almost exclusively of ostracod, gastropod and mollusk fragments. The sorting is poor, and most of the shells show moderate abrasion. The quartz and feldspar grains have an average size of 30μm, are angular and mainly detrital in nature. Any pellets present are probably faecal in origin.

Two diagenetic fabrics are present, the more common being the granular cement comprising the plasma. However, unfortunately any interpretations made are possibly invalidated to a large extent, as in many cases subsequent metamorphism has clearly affected these rocks. Still, the granular plasma is probably precipitative in origin as suggested by the following observations:

1) There is an abrupt contact between the plasma and the allochems.
2) The intergranular boundaries of the plasma are usually planar.
3) In many cases there is an increase in crystal size of the plasma away from the wall of the allochems.

The other type of fabric, drusy mosaic, occurs within most of the fossil fragments and certainly appears precipitative in origin.

Depositional Environment

The microspar wackestones have few features that are environmentally significant, and probably the best clue as to their environment will come from their association with other rock types. This is considered in Chapter 5. For now, all that can be said is that likely environments for these rocks include the low intertidal and lagoonal. This speculation is based on:

1) The complete lack of a normal marine fauna, but the presence of some, albeit very sparse, forms indicative of a restricted marine environment.
2) The absence of any features indicative of prolonged subaerial exposure.

The occurrence of a few pellets, faecal in origin as opposed to skel-algal, may prove to be significant.

Terrigenous and Faecal Pelletal Wackestones and Packstones

Rocks constituting this group are extremely thin bedded to thin bedded, greyish olive (5Y6/2), internally structureless, and have a splintery or flaggy parting. They usually weather to a dark olive (5Y4/4). Invariably they are interbedded with terrigenous units or with faecal pelletal rocks, and can usually be differentiated from the latter by their colour and flaggy appearance. They are generally confined to the Flaggy Limestone Member where they form units with a maximum thickness of 2m.

Microscopically they are typified by a relative abundance of quartz and feldspar grains, often accompanied by an appreciable amount of faecal pellets, occurring for the most part in a fine-microspar plasma. Rock fragments are invariably present (Plate XVI, 2).

Except where cleavage or twinning is apparent or an optical figure forthcoming, the quartz and feldspar grains are indistinguishable. As a consequence they are grouped together and discussed simultaneously which is reasonable, as in most cases they occur together. Apparently their average grain size increases as their relative abundance increases, and accordingly varies from 40μm - 70μm. They are invariably angular and occur in two habits, one being as squarish or rectangular grains, the other as much finer lath-shaped grains. Any definitely recognisable quartz grains are always water-clear, free of inclusions and occasionally, display overgrowths. They are monocrystalline with a straight or wavy extinction. The feldspar grains are notably fresh, the only conspicuous alteration being minor vacuolization. Both types of grain are mainly detrital in origin.

The plasma is composed of translucent, xenotopic to idiotopic equigranular calcite ranging in size from 6μm to 20μm, but with common porphyrotopes up to 40μm. Often it has a distinctly scruffy appearance due to the presence of argillite, chert and volcanic rock fragments. When the plasma is finer, faecal pellets, often coated with limonite, abound and then the rocks resemble the pelletal wackestones and packstones. On the other hand, when the plasma is coarser, the quartz and feldspar grains are so plentiful that the rocks grade towards calcareous sandstones.

Other grain types are present but only in small amounts. They include conspicuous euhedra and spheroidal clusters of pyrite, and skeletal fragments. The latter consist of poorly sorted and moderately abraded ostracod, mollusk and gastropod debris. Occasionally the ostracod shells show faint signs of alignment.

Diagenetic fabrics are poorly displayed and consist of the granular cement making up the plasma, and the drusy mosaic within the skeletal debris. Applying the relevant criteria with the usual reserve, it seems both types are neomorphic.

<u>General Depositional Environment</u>

Apart from an abundance of quartz these rocks are petrologically very similar to the faecal pelletal rock type, and in the field are closely associated with it. Therefore, they are considered to have formed in the low intertidal zone concomitant with a pronounced influx of terrigenous material. In a general way this fits in with the situation along the eastern margin of Shark Bay, where admixtures of terrigenous material are most common in the sediments from the low intertidal areas (Davies, 1970).

<u>Micritic Mudstones</u>

Composing this rock type are extremely fine, dark grey to black, essentially unfossiliferous, thin- to medium-bedded strata. These are internally structureless and have a blocky parting. Occasionally they occur as isolated nodules enclosed by dark shales. Their distribution is limited to the Micritic Limestone Member, where they form units with a maximum thickness of 8m.

Thin section work reveals a micritic plasma and a virtual absence of allochems (Plate XVII, 1). The plasma displays a marked lack of transparency and consists of dense brownish cryptocrystalline calcite with an average size of 3μm. In most cases it has a faint clotted texture, which is probably pelletoid. The most common grains are scattered angular quartz and feldspar euhedra with an average size of 15μm. Skeletal debris is absent except for a few heavily recrystallized ostracod and gastropod fragments, and for a few rare occurrences of the encrusting filamentous algae, Sphaerocodium sp., displaying spherical gonidia, partly to completely filled with calcite (Plate XVII, 2).

No conspicuous diagenetic fabrics are present.

General Depositional Environment

A shallow, yet quiet-water environment is postulated for this rock type for the following reasons:

1) The occurrence of the blue-green alga, Sphaerocodium sp., indicating an environment within the photic zone. According to Johnson (1961), calcareous algae range in depth from close to tide level down to about 50m, with optimum development between 5m and 10m.
2) The micritic nature of the beds.

The absence of fauna, except for algae, suggests a restricted, possibly lagoon-like environment, which may have been slightly more saline and more stagnant than the one in which the mollusk-gastropod wackestones formed. (See p.49.) On a gross scale, a modern-day analogue is provided by the sheltered shelf lagoon to the west of Andros Island in the Bahamas (Purdy, 1963).

Gastropod Wackestones

Grouped here are rocks packed with intensely reworked gastropod fragments ranging in size from 1mm - 8mm. The strata are thin to medium bedded and have a blocky to flaggy parting. They weather either to a distinctive light bluish grey (10BG7/1) or to a pale yellow (5Y7/3). Typically they are represented as bands between 5cm and 20cm thick, often intercalated with calcretes and occasionally with algal limestones. They occur almost exclusively within the Yellow Limestone Member.

Internally they are structureless except for desiccation cracks, which are quite common. Invariably these have more or less vertical walls and in many cases can be traced to the bedding plane surfaces, where they define polygonal columns, ranging in diameter between 5cm and 15cm. Usually the thicker the beds, the deeper and wider the cracks, and the larger the polygons.

As in the hand specimen, in thin section also, distinctive-looking gastropod fragments are the outstanding feature (Plate XIX, 1). Many of these are partially to completely infilled with very fine equigranular grey microspar. This is demonstrably different from the material of the matrix and suggests that the fragments initially accumulated in a different environment and were subjected to subsequent transport. This fits in well with the theory that many of the conspicuous microspar patches in these rocks were originally, completely sediment-infilled gastropod debris, that underwent considerable transport and lost all vestiges of former skeletal structure. However, in many cases there is a complex relationship between the microspar sediment and any drusy mosaic that may be present within the fragments.

One explanation is that the introduction of sediment and formation of drusy mosaic were more or less concurrent events.

The plasma consists of brown micritic to very fine-grained microspar, which is inequigranular and hypidiotopic. Many angular quartz and feldspar grains with an average size of 20μm are scattered throughout this plasma, but skeletal debris, apart from the gastropod fragments, is lacking.

The two diagenetic fabrics present probably differ in origin. Thus, whereas the fine granular calcite of the plasma is most likely neomorphic, the drusy mosaic of the gastropod debris is almost certainly precipitative in nature.

Depositional Environment

The presence of mudcracks indicating intermittent exposure to the atmosphere, and the complete lack of an indigenous fauna, suggests that these rocks formed in either a supratidal or high intertidal environment. Possibly they formed in both environments in depressions, into which gastropod fragments were periodically dumped by storm waters. Such an interpretation is highly speculative, and there are no references to similar rocks in the literature.

Mollusk-Gastropod Wackestones

At many localities these rocks form prominent outcrops. They consist of grey thin-bedded to very thick-bedded strata that have a blocky parting. Internally they are structureless, except in a few cases when they exhibit small-scale planar or trough cross-bedding. This consists of sets of cross-strata ranging in thickness from 5cm - 20cm. They occur sporadically, mainly throughout the Bluff Limestone and Upper Fossiliferous Limestone Members and form units up to 2m thick. In many cases they are closely associated with skeletal wackestones and packstones.

Thin sections show that the plasma is composed of dense, light brownish and equigranular calcite grains in the 2μm - 20μm range. The finer rocks in this category are therefore micrites, and these occasionally exhibit a clotted texture. Rather surprisingly these do not grade imperceptibly into fine microsparites, as there is a noticeable jump in grain size from about 3μm - 6μm. This feature has been noted by many other workers (Folk, 1965, fig.8, p.32).

The fauna is rather sparse and rather restrictive in nature. It consists almost entirely of gastropod, ostracod and mollusk fragments, the latter displaying the usual micritic envelopes. The rest of the fauna is made up of brachiopod, trilobite and possibly calcisphere debris. Many of the shells are broken and badly worn (Plate XIX, 2), although this is not always the case. Sorting is poor with a size range of 250μm - 2700μm. The only marked replacement occurs in the mollusk fragments, which show small-scale alteration by hematite and feldspar. The latter, however, usually occurs as detrital grains with a notably fine average grain size of 30μm. The quartz grains display a similar average size and habit.

Drusy mosaic is the only conspicuous diagenetic fabric present and occurs within skeletal fragments. All these are heavily recrystallized.

<u>Depositional Environment</u>

These rocks are considered to have formed in a semi-protected back-reef type of environment. The reasons for this are as follows:

1) The presence of a moderately diverse fauna, but one, nevertheless, rather restrictive in nature. This suggests water conditions not fully marine, as would pertain on the littoral side of any type of marine

barrier inhibiting circulation.

2) The original micritic nature of the rocks indicates they formed in a quiet environment. The presence of an impoverished marine fauna, however, suggests this environment was subjected to moderate aeration by circulating waters, whilst the occurrence of cross-bedding at several localities, indicates intermittent vigorous current activity.

The fragmentation exhibited by the fossil debris is probably attributable to the extensive activities of burrowing organisms (Swinchatt, 1965). These left many of the fossils randomly oriented and patchily distributed throughout the mud.

A likely ancient analogue is provided by the burrowed fragmental facies of the Blackjack Creek Formation of Pennsylvanian age in Missouri (Neal, 1969).

Skeletal Grainstones

These rocks consist of grey to dark grey (N5-N3) extremely fossiliferous beds. They are thin to medium bedded, internally structureless and have a blocky parting. Very rarely they occur as isolated nodules enclosed by dark shales. Megascopically, brachiopod, crinoid and echinoid debris dominates the fauna. The beds have a very patchy distribution and never form units thicker than 250cm.

In thin section the plasma is seen to consist of translucent, xenotopic calcite grains ranging in size from 25 m - 100 m. It exhibits five diagenetic fabrics, the two major ones being granular cement and the syntaxial overgrowths on echinoid and crinoid debris. There is little doubt that these overgrowths grew freely out into open pore spaces and can be considered as a true cement. Evidence for their precipitative nature is indicated by the following observations:[1]

[1] Inconclusive results were obtained with the cathodo-luminescence microscope, probably due to the short time spent on experimentation.

1) The outer boundaries of the rims are in contact either with other rims, granular cement or with allochems (Plate XX, 1).
2) The boundaries between the rim and granular cement are planar (Plate XX, 2).
3) The mosaic resulting from the overgrowths has planar intergranular boundaries.
4) The rims very rarely transect allochems.

Some of the rims, however, may be neomorphic in origin (Plate XXI, 1), but such cases are generally equivocal and very rare.

Granular cement is much less widespread than the overgrowths, but, like them, is precipitative in nature. Its plane intergranular boundaries, its sharp contact with the margins of allochems, and its increase in crystal size away from these, plus the three dimensional packing and good sorting of the allochems, provides some of the usual and standard criteria for this assertion (Stauffer, 1962).

Of the other types of diagenetic fabric, drusy mosaic is by far the most common. This occurs within most of the skeletal debris and is generally precipitative in nature, although excellent examples of neomorphic recrystallization may sometimes be seen. The other two fabrics, encrusting and fibrous, are very rare. The former type exhibits two habits, the more frequent being fibrous fringes oriented perpendicularly to pelletal surfaces (Plate XXI, 2). The other habit is as relatively thick and lumpy crusts, composed of equant calcite crystals growing on skeletal surfaces (Plate XXII, 1). Both types are probably precipitative. This interpretation is based mainly on their tendency to cut across other fabrics, which is itself evidence for at least two phases of diagenetic calcite.

Fibrous calcite occurs as enveloping layers of long fibrous calcite crystals around organic debris, and is only present in rocks from the uppermost part of the Cavan succession. These are frequently highly cleaved, and it is possible that this fabric formed as an initial response to metamorphosing conditions. However, it bears no resemblance to spar which is so common in marble, the usual product of the metamorphism of limestone. This may mean the fibrous calcite is neomorphic, but it must be admitted that really its origin is most obscure.

Skeletal debris is both abundant and diversified and includes the same faunal types, in approximately the same relative proportions, as the skeletal wackestones and packstones (Plate XXII, 2). Crinoid and echinoid debris is preeminent, and as well as displaying multitudinous syntaxial rims, occasionally shows the effects of pressure solution. Most of the fragments are brownish in colour, non-corroded and exhibit excellent lamellar twinning. However, in some cases (which become more common towards the top of the Cavan Limestone), intense recrystallization has obliterated all but "negative" relics of these fragments. In some instances it becomes extremely difficult to distinguish them from spar that has been severely recrystallized.

Mollusks (with the usual micritic rims) are also very abundant and quite often the shells show marked lineation, and so emphasize the moderate to good sorting that exists in these rocks. In some cases the gastropods are infilled with dense, very fine microspar (Plate XXIII, 1), and attest to redeposition in a higher energy environment. Moreover, it is not inconceivable that such infilled gastropod chambers could, following abrasion and disintegration, form structureless and cryptocrystalline masses of calcite, resembling any one of the various types of pellet.

Quartz and feldspar grains are invariably present but in very small amounts. They have an average size of 40μm and are generally detrital in nature. However, some of the feldspar is authigenic and selectively replaces the odd brachiopod shell or occurs as a rare grain in the matrix. Replacement by limonite and hematite is much more prevalent, but not severe as only the margins of skeletal tests are affected, these being mainly molluskal. Hematite is also present as fairly abundant euhedra, and limonite also occurs as a coating on any pellets that may be present. Pyrite is notably rare.

Intraclasts are also rare, but still more common in this rock type than in any other. In most cases they consist of dense brown micritic mudstone, which is structureless or has a clotted texture. However, they may be slightly coarser grained and contain unidentifiable skeletal debris and scattered quartz and feldspar grains. In many cases they are rounded and some parts of their margin may by stylolitic.

<u>General Depositional Environment</u>

Like the skeletal wackestones and packstones, these rocks are thought to be shallow subtidal in origin. However, they seem to have formed in a higher energy environment. This is indicated by the absence of any fine carbonate plasma due to winnowing out of fines, by the scarcity of any accessory minerals such as pyrite whose formation depends on at least local reducing conditions, by the sorting and abrasion of skeletal debris, and by the presence of intraclasts. The beds represent times of optimum conditions for the development of echinoids and crinoids, which may have flourished as skeletal banks.

Skeletal Micritic Wackestones

Grouped here are rocks that are very similar in outcrop appearance to the micritic mudstones (see p.45), except that they are noticeably fossiliferous. Their distribution is limited to the Micritic Limestone Member, where they form units up to 2m thick.

Microscopically, they are typified by a micritic to very fine-microspar plasma and an abundance of skeletal fragments (Plate XXIII, 2). Like the micritic mudstones, the plasma shows a marked lack of transparency. It consists of brownish, xenotopic to hypidiotopic calcite grains in the 2μm - 8μm range. Strictly speaking, then, not all these rocks are micrites. However, the great majority are, and this is why the group as a whole is termed micritic. As in the mollusk-gastropod wackestones, there is a noticeable jump in grain size from about 3μm - 6μm. Porphyrotopes are rare.

The skeletal debris is dominated by echinoderm plates and columnals, mostly crinoid, distributed randomly throughout the rock. These are algally non-corroded and do not display any overgrowths. Mollusk, gastropod, brachiopod and bryozoan fragments are present in minor amounts. These have a general fragmented appearance and are noticeably poorly sorted, ranging in size from 200μm - 8000μm.

Quartz and feldspar grains are scattered throughout but are negligible in amount. The only conspicuous diagenetic fabric is the drusy mosaic within some of the fossil fragments.

Depositional Environment

The lack of any sedimentary structures suggestive of subaerial exposure, and the presence of a fully marine biota, indicate that these rocks were laid down below the low tide mark. The prevalence of the very fine plasma and the absence of any sparry calcite does not necessarily imply that the environment lacked currents of appreciable strength or persistence. As pointed out by Cain (1968), dense echinoderm colonies, as well as producing their own sediment, form very efficient baffles, so that even in very shallow turbulent waters much fine sediment might be precipitated, when normally it would have to travel first to deeper quieter conditions. Were fine sediment to be excluded from echinoderm "build-ups" by virtue of their baffle action, so would fine suspended organic matter, and the colony would not survive (Ager, 1963). Bearing this in mind, it is significant that these rocks are similar to parts of the Fenestrate Bryozoan - Brachiopod Zone of the Jeffersonville Limestone, Indiana (Perkins, 1963), and to those rocks laid down during the lagoonal to early bank phase in the genesis of a Devonian lagoonal bank near Alpena, Michigan (Tyler, 1969). In the first case, the interpretation is that the waters were choked with thickets of echinoderms and bryozoans, entrapping a considerable quantity of micrite. The rocks also bear a close resemblance to the interbioherm[1] facies of the Lower Mississippian bioherms of southwestern Missouri and northwestern Arkansas (Troell, 1962). This facies was deposited in areas outside the immediate environmental influence of the bioherms. All this suggests the rocks may have formed as echinoderm banks or in the general vicinity of bioherms. On the other hand, their environmental interpretation may be more straightforward. They may have accumulated in a shallow, quiet-water, lagoonal environment. If the waters were poorly aerated, this could have led to the demise of a varied biota, but at the same time could have provided an ecological niche favourable for echinoderms. This was probably the

[1]Bioherms, as used by Troell, refers to reeflike, moundlike, lenslike or otherwise circumscribed structures of strictly organic origin, embedded in rocks of different lithology.

situation at times during the deposition of the rocks of the Brevispirifer gregarius Zone of Perkins (1963).

Whatever the environment (see Chapter 5), the absence of any systematic arrangement of skeletal debris and the general fragmental appearance of much of this debris, suggests that burrowing and scavenging organisms may have worked the sediment, disrupting, mixing and comminuting skeletal elements.

3.3 TERRIGENOUS ROCKS

These are most common near the base of the Cavan Limestone and show a general upward decrease in abundance. They consist of very thin- to thin-bedded marls, shales, siltstones and very fine sandstones. They form units up to 5m thick, but are usually interbedded with limestones on a metre scale. They may be multicoloured, but often weather greyish olive (7.5 Y6/2). Invariably they have a flaggy parting. Of most interest are the sandstones, for thin sections reveal that these are volcanic arenites. They are texturally immature and contain an appreciable amount of quartz and feldspar. The quartz grains are angular to subrounded, poorly sorted and contain few inclusions. Often they are water-clear, have straight edges but with embayments, and display slightly to strongly undulose extinction. Naturally, however, the most diagnostic feature is the relative abundance of rock fragments. These are readily recognisable due to their scruffy pale brown colouration, but their precise identification is extremely difficult. However, almost certainly they are predominantly of volcanic origin as evidenced by the occasional spherulites, gas bubbles and feldspar microphenocrysts within the fragments. Chert and quartz siltstone fragments also occur. The siltstones associated with these arenites have a kindred composition.

Sedimentary structures are lacking except for occasional laminations on a millimetre scale. These are defined by differences in quartz and feldspar concentrations.

CHAPTER 4

SUBDIVISION OF AND LATERAL VARIATIONS WITHIN THE CAVAN LIMESTONE

4.1 INTRODUCTION

As explained in Chapter 2 the Cavan Limestone has been divided into six members. The purpose of this chapter is to describe in detail the features of each of these members at four localities, within the context of the 12 carbonate rock types discussed in the preceding chapter. The four localities are at Clear Hill, and Good Hope and near Taemas Bridge and Mountain Creek Bridge (see Fig.2 and geological map).

A consequence of this approach is that extensive lateral variation within the area becomes very apparent. This leads naturally into the following chapter when an attempt is made to explain this. Also, because of this variation the choice of a type locality is very difficult, and reasons for its selection and any shortcomings are accordingly pointed out.

The percentages of each rock type shown in the text and set out for the four type localities in Table VI, are based on the frequency of individual beds and not on their thickness. Thus a certain bed may account for only 15% of the total thickness of a particular section, but have a frequency of more than, say, 40% (calcretes are a good example).

Thicknesses over 10m are rounded off to the nearest metre, whereas those less than 10m are given to one decimal place.

4.2 FLAGGY LIMESTONE MEMBER

Type Section: Clear Hill - This locality was chosen as the type section because the succession is complete (which is not the case at Taemas Bridge or Mountain Creek Bridge), and because it is much more typical of the area as a whole than

TEXT-TABLE VI. PERCENTAGE ROCK TYPES

ROCK TYPE	% ROCK TYPES																							
	Clear Hill						Taemas Bridge						Mountain Creek Bridge						Good Hope					
	I	II	III	IV	V	VI	I	II	III	IV	V	VI	I	II	III	IV	V	VI[1]	I	II	III	IV	V	VI[2]
Skeletal micritic w																40								
Skeletal grainstone		3	3						3						2		2							
Mollusk-gastropod w		32					3				1		2							11				
Gastropod w						30					7	2											27	
Micritic mudstone	2			50	6				1	72	3		7			60						80		
Terrigenous & pelletal w & p	13						17				1		11	10					3					
Microspar w					18		6	3			18				5		10		37	13			13	
Skel-algal p		25					40	72			2	63	8	30						11				
Pelletal w & p	27				5	3		12	18		4	3	2	30										
Calcrete	3				53		8				18						6		24				36	
Algal limestone	10			20	10						10		62				79						8	
Skeletal w & p		40	93	30		35	3	2	58				1	10	83					12	100			
Marl	6						13	1			10	4	1				2		33	2				
Clay									7	6	13	4							3	8		20		
Shale	19		4		8	32	7	6	13	22	11	18		10	5								15	
Siltstone	6						3	4				4	5	10	5		1			1				
Sandstone	14										2	2								42				

*Type section

[1] poorly exposed

[2] probably not deposited

I = Flaggy Limestone member
II = Bluff Limestone member
III = Nodular Limestone member
IV = Micritic Limestone member
V = Yellow Limestone member
VI = Upper Fossiliferous Limestone member

w = wackestone, p = packstone

the Good Hope Section (Plate XXIV, 1).

It comprises a sequence 47m thick. The lowermost third consists of terrigenous strata with only a few isolated interbeds of algal limestone and terrigenous faecal pelletal wackestone and packstone. As a result, the boundary between the Fifeshire Formation and the Cavan Limestone is necessarily arbitrary, and in fact is placed at the first appearance of demonstrably carbonate strata, in this case, a bed of algal limestone.

The terrigenous strata consist of very thin-bedded to thin-bedded marls (6%), shales (19%), siltstones (6%) and very fine sandstones (14%). Upwards in the succession these rapidly become less prevalent, and the sequence is dominated by faecal pelletal wackestones and packstones (27%), and to a lesser degree, by terrigenous faecal pelletal wackestones and packstones (13%), although the latter become less frequent higher in the sequence. Scattered throughout are beds of algal limestones (10%), whilst towards the top rare calcrete bands (3%) appear. The feldspar content of the rocks increases at the expense of the quartz, as the succession is ascended.

The member is essentially unfossiliferous and displays few sedimentary structures. These are generally inconspicuous and represented by a few mudcracks, cross-beds, and the S-mat type laminations of the algal limestones. Also present are laminations from 0.5mm - 2mm thick occasionally occurring in most of the rock types, both terrigenous and carbonate. These apparently are due to grain-size differences, or to increases in the silt, clay or calcite content. This feature may be emphasized by colour differences.

4.3 LATERAL VARIATIONS

At Taemas Bridge approximately the lowermost 20m of the section is not exposed. However, the remaining strata (18m) resemble the sequence at Clear Hill very closely, showing a predominance of pelletal wackestones and packstones (40% vs. 27%), and terrigenous pelletal wackestones and packstones (17% vs. 13%). The only notable differences are the infrequent presence of skeletal wackestones (3% vs. 0%), and the absence of algal limestones (0% vs. 10%). The last feature, however, may not be significant, as algal rocks are only common low down in the sequence at Clear Hill.

As regards sedimentary structures, algal laminations and cross-beds are lacking, whereas birdseye structure and a few cases of burrowing are present. These latter features are absent at Clear Hill.

The succession near Mountain Creek Bridge is completely different and much thicker (74+m[1] vs. 47m). This is due to the very thick and striking development of algal limestones (62% vs. 7%). Other major differences include the virtual absence of pelletal wackestones and packstones (2% vs. 27%), and, to a lesser degree, the presence of conspicuous, although relatively uncommon, beds of skel-algal packstone (8% vs. 0%). In addition, terrigenous strata are relatively unimportant (13% vs. 31%).

Naturally, algal laminations make up the bulk of the sedimentary structures. These are accompanied by frequent birdseye and burrowing textures.

The sequence at Good Hope is also completely different, but, in this case, is much thinner (15m vs. 47m). Its base is

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[1] Base not seen

placed at the incoming of the first demonstrably carbonate strata, in this instance, a bed of calcrete. Pelletal wackestones and packstones (0% vs. 27%), terrigenous pelletal wackestones and packstones (0% vs. 13%), and algal limestones (0% vs. 10%) are completely absent. In their place, the succession is made up predominantly of microspar wackestones (37% vs. 0%), and, interestingly, calcrete (24% vs. 3%). However, as at Clear Hill, terrigenous strata are very common (36% vs. 31%), but in this case are made up almost exclusively of marls (33% vs. 6%).

No algal laminations or cross-beds are present.

4.4 BLUFF LIMESTONE MEMBER

Type Section: Clear Hill - The succession at this type locality is by no means typical of the member in general. However, its prominent outcrop (Plate XIV, 2), well-defined base and excellent delimitation at this geologically well-known locality, together with the fact that when it occurs as medium-bedded strata, as it does at Clear Hill, it can be followed for long distances, is considered reasonable argument for its choice as the type section.

The member consists of a well-stratified, homogeneous sequence 13m thick, of fossiliferous, light grey, but often strikingly dark weathering strata, that are medium- to thick-bedded. The rocks outcrop very prominently and display a sharp contact with the underlying unfossiliferous and thinner-bedded rocks of the Flaggy Limestone Member. The most common rock types are skeletal wackestones and packstones (40%), although mollusk - gastropod wackestones (32%), and skel-algal packstones (25%) are also prevalent. Of much interest, but of rare occurrence, are the skeletal grainstones (3%).

Sedimentary structures are infrequent and consist of low angular tabular cross-beds, with sets of cross-strata ranging in thickness from 5cm - 20cm. Also present are planar laminations, 1mm - 2mm thick, produced by differences in silt content.

Although in most cases an abundant and diverse fauna is present, megascopically it is not prominent, and generally only scattered brachiopod debris is readily apparent.

4.5 LATERAL VARIATIONS

The upper part of the succession at Good Hope (18m vs. 13m) in particular, differs greatly from that at Clear Hill. Here sandstones (42% vs. 0%) are very common. They are yellowish, very fine grained, reasonably well sorted, friable and contain some brachiopod debris. The lower part of the sequence is not so strikingly different, and is composed of most of the same rock types. These include skeletal wackestones and packstones (12% vs. 40%), skel-algal packstones (11% vs. 25%) and mollusk - gastropod wackestones (11% vs. 40%). In addition, microspar wackestones (13% vs. 0%) are quite common.

The base of the succession is not well marked and is rather arbitrarily placed at the final disappearance of the calcrete beds of the underlying member. Cross-strata are absent.

The sequence near Taemas Bridge (19m vs. 13m) differs mainly in its very high proportion of skel-algal packstones (72% vs. 25%), the virtual absence of skeletal wackestones and packstones (2% vs. 40%), and the complete absence of mollusk - gastropod wackestones (0% vs. 32%). Moreover, it contains appreciable beds of pelletal wackestones and packstones (12% vs. 0%).

As at Good Hope, the base is not conspicuous and in this case is placed at the first appearance of an appreciable thickness of strata containing an obvious fauna.

Near Mountain Creek Bridge the succession (10m vs. 13m) consists predominantly of skeletal wackestones and packstones (30% vs. 25%) and pelletal wackestones and packstones (30% vs. 0%), and differs in much the same way from the type section as does the sequence near Taemas Bridge. In addition, however, the Mountain Creek Bridge section contains some beds of terrigenous pelletal wackestones and packstones (10% vs. 0%).

Cross-bedding is absent, and again the base of the succession is rather obscure and is arbitrarily placed at the final disappearance of the algal beds of the underlying member.

4.6 NODULAR LIMESTONE MEMBER

Type Section: Near Mountain Creek Bridge - This member is generally recessive and does not outcrop completely at Clear Hill. Out of the remaining localities, its nodular character can be best observed near Mountain Creek Bridge and so this was selected as the type locality. However, since the underlying rocks here are also nodular in aspect, its base is not well defined, and is rather arbitrarily positioned at the incoming of an abundant megascopic fauna.

The sequence is 48m thick and is made up almost exclusively of nodular beds of skeletal packstone set in a clay, marl or shale matrix (83%). The remainder of the succession consists of a few beds of microspar wackestones (5%), siltstones (3%), shales (5%), and skeletal grainstones (2%).

Sedimentary structures, other than the actual nodularity of the beds, are lacking, except possibly for a few cases of sedimentary boudinage and structures produced by interstratal sliding. However, the succession is richly fossiliferous, and possibly contains towards the middle of the succession a fauna that shows some faint signs of zonation. Megascopically, brachiopods, corals, crinoids and gastropods are most profuse. Laminar stromatoporoids are relatively abundant.

In the lower beds the fauna is so broken up and worn that recognition of any diagnostic forms is precluded. Notable, however, are the frequent concentrations of brachiopod debris, and the occurrence of the tabulate coral, Favosites murrumbidgeensis, which is extremely abundant at some levels, but which tends to become less common higher in the succession. Crinoid ossicles, echinoderm plates, orthoconic nautiloids, gastropods, occasional Tentaralites, and rare bivalves make up the rest of the fauna.

Towards the middle of the succession the fauna becomes even more abundant and here the corals, Cystiphyllum sp. and, to a lesser degree, Zelolasma gemiforme are particularly plentiful. Some laminar stromatoporoids are also present. In addition, there are rare occurrences of the corals Tipheophyllum bartrumi and Chalcidophyllum sp. This is probably the Cystiphyllum zone of Browne (1959).

Brachiopods are also common within these beds but come into their own slightly higher in the succession. Here there is a development of black, argillaceous and somewhat carbonaceous limestone beds, which are packed full with the spiriferid Hypothyridina aff. cuboides. These are accompanied by the chonetids Parachonetes sp., Protochonetes sp. and Protochonetes aff. P. culleni. Two specimens of the athyrid Howittia multiplicata were also found. Apparently this is Browne's (1959) Hypothyridina zone.

Like the lower beds, the strata above the black limestone beds tend to contain fossil debris very difficult to identify. However, in all probability it is essentially similar to that below, but possibly has a richer gastropod fauna.

While there appears to be a particular concentration of most of the forms just mentioned near the middle of the succession - probably due to optimum living conditions - they are by no means restricted to any one group of beds. On the contrary most forms, for example, Hypothyridina, range right throughout the member. Nevertheless, it seems reasonable to recognise a Hypothyridina zone overlying a Cystiphyllum - Zelolasma zone. This is at variance with Browne's (1959) ideas. She recognised a Cystiphyllum zone (bottom), a Hypothyridina zone and a Zelolasma zone.

At several levels within the succession,the beds show clear evidence of having formed essentially in situ. However, in most cases no evidence is present that the beds ever constituted wave-resistant structures, and so these are best described as marine banks.[1] They are invariably made up predominantly of echinoid and crinoid remains. In those cases where some evidence is forthcoming, the colonies are composed almost entirely of the coral Cystiphyllum sp. (Plate XXV, 1), but still do not have the form or scale of reefs. Nevertheless they are often flanked by spar grainstones composed of very coarse skeletal debris, some shells being up to 6cm in size. Moreover, some grains are algally-coated with concentric layers of sediment, and constitute a distinctive type of algal structure called oncolitic, in this case the ss, mode C type of Logan, Rezak and Ginsburg (1964). According to this team of workers,

[1] Defined as a skeletal deposit formed by organisms which do not have the ecological potential to erect a wave-resistant structure (Nelson, Brown & Brineman, 1962).

such conditions indicate more or less continual motion, and such conditions could certainly have prevailed on the flanks of these Cystiphyllum colonies. The stromatoporoids present throughout these rocks probably contributed to the production of the structures by the binding of sediment. In conformity with the definitions of Nelson et al. (1962), these Cystiphyllum colonies are "reefy biostromes" : "reefy" because the Cystiphyllum seem to have been potentially wave-resistant, and "biostromes" because the height-to-length ratio of the structures is extremely low, and nowhere do they actually project upwards into overlying strata. The plasma of these rocks is relatively fine even where Cystiphyllum is extremely abundant, and the biostromes may well have acted as baffles to the high energy currents. Thus it would have been possible for fine material to accumulate in some of the patches and crevices between branching organisms, where quiet water conditions could exist.

4.7 LATERAL VARIATIONS

In sharp contrast to the members just described, the Nodular Limestone Member shows very little variation in lithology, and is invariably composed of dominantly, commonly nodular, skeletal wackestones and packstones, sometimes almost to the exclusion of other rock types. In fact, at Good Hope the succession (23m vs. 48m) consists entirely of these nodular skeletal rocks (100% vs. 81%). At Taemas Bridge (25m vs. 48m), however, pelletal wackestones and packstones (18% vs. 0%) are quite common, and as a result the skeletal rocks, which here are not so much nodular as interbedded with shales and clays, are correspondingly less predominant (58% vs. 81%). This is not the case at Clear Hill (23m vs. 48m) where once again, the skeletal rocks are extremely abundant (93% vs. 81%).

Interestingly, a few beds of skeletal grainstones (maximum 5% near Mountain Creek Bridge) occur at each of the localities, except Good Hope.

The type section shows the best evidence for organic "build-ups". However, a <u>cystiphyllum</u> biostrome possibly also occurs within the Taemas Bridge sequence, about 2m above the base, whilst the hummucky strata much in evidence at Clear Hill may be similar structures poorly preserved. It is stressed again that the nodular limestones are everywhere extremely fossiliferous, and are probably organically constructed at many places, but this is difficult to prove. The common hummucky appearance of the beds might be due to such organic "build-ups".

As at Mountain Creek Bridge, the base of the sequence at Taemas Bridge is arbitrarily positioned at the incoming of an abundant megascopic fauna. At Clear Hill and Good Hope, however, the boundary is well defined, as in the first case the beds are extremely nodular and overlie a well-stratified sequence, whereas at Good Hope, the beds rest on a thick terrigenous unit.

<u>4.8 MICRITIC LIMESTONE MEMBER</u>

Type section: Mountain Creek Bridge - This locality was chosen because the sequence here is completely exposed and well delimitated. It has a thickness of 13m and is made up of both loose nodular and compact nodular beds. These consist of dark micritic mudstones (60%) and dark skeletal micritic wackestones and packstones (40%), set in a dark shale matrix. Apart from the nodularity of the beds themselves, sedimentary structures are lacking. Generally organic remains are very sparse, but in some of the wackestones, megascopic debris, represented mostly by echinoderm fragments, is abundant.

It is evident that these beds are structurally identical to those of the underlying member. However, their extremely fine-grained nature and dark colour are most diagnostic, and facilitate the demarcation of a sharp boundary between the two sequences. Above, the beds pass sharply into the algal limestones of the Flaggy Limestone Member.

4.9 LATERAL VARIATIONS

The succession at Clear Hill (5.4m vs. 13m) differs the most from that at the type locality. Thus, although it consists predominantly of micritic mudstones (50% vs. 60%), which are often nodular, skeletal wackestones and packstones (30% vs. 0%) and algal limestones (20% vs. 0%) are also conspicuous. Moreover, beds of skeletal micritic wackestone (0% vs. 40%) are absent. This last feature is also the case at Taemas Bridge (6.6m vs. 13m) and Good Hope (6.3m vs. 13m). Apart from this, the succession at these two localities is essentially similar to the type sequence, in that they consist for the most part of micritic mudstones (72% vs. 60% and 80% vs. 60% respectively). These are mostly nodular at Taemas Bridge, but are interbedded with clays at Good Hope.

As regards sedimentary structures, only the Good Hope sequence is notable in that it displays some mudcracks. At all localities the base of the succession is well marked by the incoming of dark micritic rocks.

4.10 YELLOW LIMESTONE MEMBER

Type location: Good Hope - The succession here is well exposed and fairly typical of the lithology in general, and so affords a good type section. It consists of thin-bedded, often flaggy, yellow-weathering strata and has a thickness of 26m. Evenly distributed throughout are prominent calcrete bands (36%) and beds of gastropod wackestone (27%), whereas algal limestones (8%) are confined to the lower half of the succession. Microspar wackestones (13%) and terrigenous interbeds (15%) are only common towards the top of the sequence. Of great interest is a unit 1.5m thick and near the top of the succession, that consists of red soil with a few scattered and broken bands of calcrete. This may be a paleosol.

Fossils are lacking except for the conspicuous gastropod intraclasts of the gastropod wackestones, and except for rare leached brachiopod debris near the top of the succession.[1] However, sedimentary structures are fairly common. Prevalent amongst these are the S-mat type laminations of the algal limestones. In many cases these are distorted and broken up to varying degrees, attesting to the desiccation that once took place in these rocks. This is further demonstrated by the occurrence of polygonal mudcracks and birdseye. Other structures include the planar laminations present in some of the calcrete bands, and the 1mm - 2mm thick laminations due to differences in terrigenous content that occur in many of the rock types.

The sequence passes sharply into nodular, dark micritic beds of the underlying member, from which it is thus easily differentiated. Upwards it passes directly into the red shales and siltstones of the Majurgong Formation, there being no Upper Fossiliferous Limestone Member. This change is not conspicuous as there is much red soil, which may represent a paleosol unit in the vicinity of this boundary.

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[1] The view could be taken that this brachiopod debris marks rocks belonging to the Upper Fossiliferous Limestone Member. However, since it is extremely sparse and since calcretes occur throughout, it seems more reasonable to consider it as part of the Yellow Limestone Member.

4.11 LATERAL VARIATION

This sequence shows the most variation in lithology of all the members in the Cavan Limestone. The rocks near Mountain Creek Bridge (56m vs. 26m) differ the most from those at the type section. This is due to the very thick development of algal limestone (79% vs. 8%) there, and to a lesser degree, to the scarcity of calcrete (6% vs. 27%). In addition, gastropod wackestones (0% vs. 36%) are completely absent. On the other hand, the sequence at Clear Hill (23m vs. 26m) is very similar to the type section, the only major difference being the absence of gastropod wackestones (0% vs. 34%).

A great range in rock types is seen at Taemas Bridge (26m vs. 26m), but apart from a noticeable increase in terrigenous strata (36% vs. 15%), in a general way the sequence is again similar to the type section in that it consists of the same rock types. The only major difference is a reduction in the number of gastropod wackestone beds (7% vs. 36%).

The sequence at Mountain Creek Bridge shows the best development of sedimentary structures, and in addition to those displayed at the type locality, which are duplicated rather closely at Taemas Bridge and Clear Hill, includes t-mat laminations, burrows, teepee structures, and graded bedding.

The base of the sequence is invariably well defined and, apart from the rocks at Taemas Bridge where it is delimitated by the incoming of yellow weathering gastropod wackestones, it is marked by the appearance of algal strata (Plate XXV, 2).

4.12 UPPER FOSSILIFEROUS LIMESTONE MEMBER

Type locality: Taemas Bridge - This is the most poorly exposed member within the Cavan Limestone. As a result, Taemas Bridge was selected as the type locality, not so much because it represents the typical lithology, but because the succession there is well exposed. This is 14m thick and consists almost entirely in the lower half of medium-bedded skel-algal packstones (63%). These are often intercalated with clay units about 5cm thick. Towards the top, terrigenous beds (32%) become increasingly more prevalent. Most of these are yellowish to grey shales (18%), which are thinly bedded and have a blocky parting. A few bands of pelletal wackestones and packstones (3%) also occur here.

The beds are sparsely fossiliferous and megascopically, only leached brachiopods, both whole and fragmented, are conspicuous. However, their presence is diagnostic.

Sedimentary structures are rare and consist of a few occurrences of low angular cross-beds, with sets of cross-strata ranging in thickness from 5cm - 10cm. Also present are planar laminations within the skel-algal rocks. These are 1mm - 2mm thick, and due to differences in terrigenous content.

The sequence passes sharply down into calcretes and microspar wackestones of the Flaggy Limestone Member. Above, the base of the Majurgong is well marked by the rapid incoming of red shales and siltstones.

4.13 LATERAL VARIATIONS

At Clear Hill (10m vs. 14m), skel-algal packstones are absent (0% vs. 63%), but, as at the type section, the rocks are obviously sparsely fossiliferous. However, in this case they are composed mainly of skeletal wackestones (35% vs. 0%) and mollusk-gastropod wackestones (30% vs. 0%). There is also an increase in terrigenous strata (32% vs. 14%). The lower boundary is well defined by the incoming of fossiliferous strata. However, the upper beds are very poorly exposed and the boundary is not seen. Nevertheless, it is arbitrarily drawn at the first appearance of a few isolated flags of yellow sandstone.

Likewise, the succession is very poorly exposed at Mountain Creek Bridge (7m vs. 14m), and only the lowermost one metre can be observed. This consists of algal rocks and skeletal wackestones. The latter rest abruptly on the algal limestones of the underlying member. The boundary with the Majurgong Formation is placed approximately as at Clear Hill, at the first appearance of a few flags of yellow sandstone.

At Good Hope the member is missing (probably it was not deposited).

Sedimentary structures are at a minimum throughout this member, and except for those seen at the type section, consist only of a few algal laminations as occurring near Mountain Creek Bridge.

CHAPTER 5

ENVIRONMENTAL RECONSTRUCTION OF THE CAVAN LIMESTONE

5.1 INTRODUCTION

In preceding chapters the Cavan Limestone has been defined and discussed mainly in terms of 12 carbonate rock types. It has then been divided into 6 members, based principally on the vertical distribution of these rock types at 4 localities. This chapter is concerned primarily with the lateral distribution of these rock types.

It is apparent from Chapter 4 that there is very extensive lateral variation within the Cavan Limestone. On its own, a simple transgression-regression hypothesis is not adequate to explain this. Among other things, this hypothesis assumes that:

1) Sedimentary facies and organisms bear a simple relationship to water depth and distance from shore.
2) Depth and distance from shore bear a simple relationship to each other.
3) The rate of transgression or regression is slow enough, so that under local conditions of sedimentation and subsidence a recognizable stratigraphic record will be formed.

While this may have been the case, for instance during parts of the Cenozoic along the northern margin of the Gulf of Mexico (Israelsky, 1959), conditions of deposition are strikingly different in the shallow waters of the Great Bahamas Bank. Here the true controls over sedimentation are related to mass circulation rate and level of turbulence, factors which are in turn complex functions of the geography and hydrography of the Bank as a whole. In addition, depth and distance from shore bear no simple relationship to each other (Laporte, 1964). Such a situation is best studied using a facies-migration approach. This assumes that the depositional record at any one place and time reflects primarily the local basinal hydrography, rather than a particular phase in a completely recorded cycle of transgression or regression (Laporte, 1964). Applying this approach to the analysis of the Cavan Limestone, it follows that the extensive lateral variations were caused by lateral migrations and overlaps of coexisting, laterally adjoining facies, giving complex facies mosaics (Laporte, 1967). Furthermore, at any one point in time, there were (in theory) 12 major carbonate facies corresponding to the 12 rock types described in Chapter 3. Here an attempt is made to reconstruct their distribution, together with that of five terrigenous facies, by constructing a depositional model. Firstly, the major environments within the overall depositional regime are considered using the inferences gained from Chapter 3. These are then viewed again within the context of a rigorous search for more subtle relationships using a Markov analysis, which should enable possible 3-dimensional arrangements of the various rock types to be inferred. This step eliminates to an appreciable degree, the presentation of a predominantly impressionistic depositional model.

5.2 GENERAL ENVIRONMENTS

The occurrence within the Cavan Limestone of extensive yellow-weathering, burrowed, algally-laminated, and desiccated strata records, in part at least, carbonate tidal flat conditions similar to those described, for instance, for parts of Shark Bay, Western Australia (Logan, Davies, Read & Cebulski, 1970) and for the Bahamas and South Florida (Ginsburg, 1964; Purdy & Imbrie, 1964), and also postulated for many ancient tidal flats (Freeman, 1972; Fagerstrom & Burchett, 1972; Kepper, 1972). The calcrete beds are most significant as they attest to considerable periods of emergence. On the other hand, the grey-weathering, highly fossiliferous, occasionally biostromal beds, point to the existence of marginal shallow-water conditions.

In addition, some of the rocks are fine grained, dark in colour, and contain an impoverished fauna - in fact look typically lagoonal. This implies the existence of an offshore barrier which served to restrict circulation, and to limit hydrokinetic energy. Such a barrier could originate either from the interaction of physical environmental factors and bathymetry, or from the presence of some type of organic community. One type is the reef community consisting of frame-building organisms that can raise a prominence into the zone of wave action. Another type lacks rigid frame-builders but either furnishes a greater supply of skeletal grains than is contributed by organisms in the surrounding areas (Lowenstam, 1950), or consists of sediment baffling organisms that account for differential accumulation of sediment.

In the case of the Cavan Limestone physical and biological mechanisms probably both contributed. Thus restriction of circulation, by analogy with some modern tidal flats, and from the consideration of both Shaw's (1964) and Irwin's (1965) models for epeiric clear water sedimentation, may have resulted from the low order of slope and width of the Cavan Limestone tidal flat. The activity of organic communities, also seems applicable, as Cystiphyllum biostromes and echinoderm banks (p. 55) existed during the deposition of the Cavan Limestone. It now follows that the interaction of physical environmental factors, enhanced by the presence of organic "build-ups," may explain the lack of sparites in the shallow subtidal rocks of the Cavan Limestone. This could only be vaguely guessed at in Chapter 3. In fact, following Irwin (1965), the whole of the Cavan Limestone was deposited in a low energy environment. However, the usefulness of his model is strictly limited here, as it has to be greatly reduced in scale to be completely applicable, and because it does not take into account appreciable volumes of terrigenous influx.

Finally, almost certainly the relationships between the carbonate rock types are influenced greatly by the presence of terrigenous detritus.

In summary then, it seems that any environmental reconstruction of the Cavan Limestone must encompass a depositional regime, ranging from the high supratidal to the shallow subtidal, the latter being lagoonal and biostromal in parts. Modifications to varying degrees by terrigenous influx should be emphasized.

5.3 MARKOV ANALYSIS

A Markov process is a "stochastic process which moves through a finite number of states, and for which the probability of entering a certain state depends only on the last state occupied" (Kemeng & Snell, 1960). In other words, the probability of event B following event A, while not a certainty, is distinctly greater or lower than that predicted by pure chance. This implies a 'memory' effect, in that transitions from one rock type to another may be dependent on one or more immediately previous events. In actual fact, many depositional processes appear to be Markovian. For example, the probability of deposition of a coal bed may depend on whether an underclay was previously deposited. Several papers can be consulted for more detailed discussions regarding this technique (Potter & Blakely, 1968; Krumbein, 1967).

In most cases, a Markov analysis is used to investigate any cyclicity that may be present within a succession (Gingerich, 1969; Allen, 1970; Lumsden, 1971). Moreover, in most cases it is used within the context of a 2-dimensional analysis, that is, it is employed primarily in the study of the vertical profile. Certain factors limit the usefulness of this approach for the Cavan Limestone. Firstly, the large number of rock types, 17 in all, (compared, for example, with 4 used by Gingerich) greatly complicates the search for relationships. Secondly, and of more importance, the obviously extensive lateral variations that existed during the deposition of the Cavan Limestone, are anything but conducive to any process that rigorously interrogates for cyclicity. This is because any process or set of processes operating periodically, will not give rise to uniform reciprocal changes in the facies or rock types along the depositional strike, simply because any changes will depend more on very localised changes in such factors as the hydrography of the area, which varies in a random way. Nevertheless, the overall imprints left by any periodic changes should be apparent. These are discussed in the next chapter. Moreover, the presence of cyclicity is suggested (but not shown per se) by the chi-square values, calculated for the sequence at the four type localities. (See p.79.)

So, while its limitations within a 2-dimensional framework are apparent, the analysis still finds much use as an aid in the 3-dimensional environmental reconstruction of the Cavan Limestone. The rationale behind this is that rock types that are shown to be closely related from the Markov analysis, probably were adjacent or close to each other on the ancient tidal flat and surrounding areas. It is a strictly mathematical treatment. Nevertheless, it is still conceded that the final reconstruction will contain an impressionistic element. This enters during construction of the tree diagram that depicts the relationships between rock types. (See below.)

Procedure

The analysis was carried out using the computer program MARKTEST, a listing of which appears in Appendix I. This program is adapted from the Testmark program of Krumbein (1967). It is designed to carry through the steps of a Markov analysis as outlined by Gingerich (1969), including a chi-square test for significance.

From the detailed logs (Logs I-IV) drawn up for the Cavan Limestone at each of the type localities, a first-order facies transition count matrix (Table VII) is constructed, within the context of the 12 carbonate rock types and 5 terrigenous rock types, the latter being marl, clay, shale, siltstone and sandstone. This matrix simply shows the number of times a certain rock type (say type A) passes up into another rock type (say type B), and is used as the input for the MARKTEST program. From this a transition probability matrix (Table VIII), an independent trials matrix (Table IX), and a difference matrix (Table X) are computed. The first records the observed probability of occurrence of each transition, and is obtained by taking, for example, the number of transitions of bed A to bed B, and dividing by the total number of upward transitions commencing with bed A. The second matrix shows the chance of occurrence of each transition if the transitions were a function of random processes, for example, if the beds were randomly interstratified. In this matrix the probability of the transition A upwards to B is computed by dividing the total number of B beds by the total number of non-A beds. By subtracting the second matrix from the first, the difference matrix is obtained. The positive values here represent those transitions that have a higher than random probability of occurrence.

Calculation of the chi-square values is as follows (Gingerich, 1969):

$$\Sigma_{ij}\frac{[f_{ij} - f_i(e_{ij})]^2}{f_i(e_{ij})}$$

where f_{ij} is the observed frequency of an element in the transition count matrix,

e_{ij} is the corresponding element in the independent trials matrix, and f_i

is the number of units of rock type i.

This formula works out a number which compares observed occurrences (f_{ij}) versus occurrences expected if the series of events is totally random ($f_i[e_{ij}]$). A chi-square table with the proper degrees of freedom, may then be inspected to determine if the value indicates significant divergence from expectations (Krumbein & Graybill, 1965).

The values obtained from the four type localities are shown below.

Locality	X^2	Degrees of freedom	Significant to
Good Hope	276.216	168	$p < 0.0005$ limit
Clear Hill	287.693	195	$p < 0.0005$ limit
Mountain Creek Bridge	259.061	195	$p < 0.005$ limit
Taemas Bridge	267.054	224	$p < 0.025$ limit

Since $p < 0.05$ can be taken as the limit which signifies significance, clearly each succession is, in part at least, Markovian.

In the following figures and tables:

A = Calcrete

B = Gastropod wackestone

C = Algal limestone

D = Terrigenous and pelletal wackestone and packstone

E = Pelletal wackestone and packstone

F = Microspar wackestone

G = Micritic mudstone

H = Skeletal micritic mudstone

I = Mollusk-gastropod wackestone

J = Skel-algal packstone

K = Skeletal wackestone and packstone

L = Skeletal grainstone

M = Marl

N = Clay

O = Shale

P = Siltstone

Q = Sandstone

w = wackestone

p = packstone

TEXT-TABLE VII. FACİES TRANSITION MATRIX

Good Hope

	A	B	C	F	G	I	J	K	L	M	N	O	P	Q
A	0	8	2	7	0	2	0	0	0	3	3	0	1	2
B	8	0	2	1	0	0	0	0	0	1	0	0	0	0
C	1	3	0	0	0	0	0	0	0	0	0	0	0	0
F	7	1	0	0	1	2	0	0	0	8	1	1	1	2
G	0	1	0	1	0	0	0	0	0	0	2	0	0	0
I	1	0	0	2	0	0	0	1	0	0	0	0	0	0
J	0	0	0	0	0	0	0	2	0	0	3	0	0	0
K	0	0	0	0	1	0	3	0	1	0	0	0	0	0
L	0	0	0	0	0	0	0	1	0	0	0	0	0	0
M	5	1	1	8	0	0	0	0	0	0	0	0	1	0
N	3	0	0	2	2	0	2	0	0	0	1	0	1	1
O	0	0	1	1	0	0	0	0	0	0	0	0	1	0
P	1	1	0	1	0	0	0	0	0	0	1	1	0	0
Q	1	0	0	2	0	0	0	1	0	0	1	0	0	0

Clear Hill

	A	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0	0	2	1	2	1	0	0	0	0	0	0	3	0	0
C	0	0	2	6	0	1	0	0	0	0	2	0	4	1	2
D	1	3	0	6	0	1	0	0	0	0	1	0	4	1	1
E	3	7	2	0	0	0	1	0	0	0	9	0	4	2	3
F	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
G	2	1	1	0	0	0	0	0	2	0	0	0	2	1	0
I	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0
J	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
K	0	1	0	0	0	2	1	0	0	2	0	1	5	0	1
L	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
M	1	0	4	7	0	0	0	0	0	0	0	0	0	0	2
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	1	3	2	4	0	4	1	1	4	0	1	0	0	5	9
P	0	1	3	0	0	0	0	0	0	0	1	0	2	0	2
Q	0	0	4	2	0	0	0	0	1	0	1	0	8	3	0

Mountain Creek Bridge

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	0	4	0	0	1	0	0	0	0	0	0	0	0	0	0
C	5	0	5	1	1	0	0	0	2	3	0	1	2	0	1
D	0	5	0	0	0	0	0	2	1	0	0	0	2	0	1
E	0	1	0	0	0	0	0	0	0	1	0	1	0	0	1
F	1	7	0	0	0	0	0	0	0	1	0	0	0	0	0
G	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0
H	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
I	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
J	0	3	0	0	0	0	0	0	0	1	0	0	0	1	0
K	0	2	0	0	1	1	0	0	1	0	1	1	0	0	1
L	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0
M	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0
N	0	2	2	0	0	0	0	0	0	0	0	0	0	0	1
O	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
P	0	2	1	1	0	0	0	0	0	1	0	0	0	0	0

Taemas Bridge

	A	B	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0	0	2	1	4	4	1	0	1	0	0	1	6	0	0	0
B	1	0	1	0	1	1	1	0	0	0	0	2	0	1	0	0
C	0	1	0	0	0	2	0	0	0	0	0	3	3	5	2	1
D	2	0	0	0	1	0	0	0	0	0	0	1	0	3	0	0
E	3	1	1	2	0	4	0	0	3	4	0	2	0	6	0	0
F	6	0	2	1	2	0	0	0	3	0	0	1	4	3	0	1
G	0	1	0	0	1	0	0	0	0	1	0	0	2	1	0	1
I	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
J	0	0	0	0	3	3	0	0	0	0	0	1	1	2	2	0
K	0	0	0	0	1	0	1	0	1	0	2	0	4	6	0	0
L	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
M	3	0	3	1	4	2	0	1	1	0	0	0	0	4	0	0
N	3	2	3	0	0	5	0	0	0	4	0	4	0	5	0	0
O	3	2	3	0	6	2	3	1	2	4	0	2	4	0	1	2
P	0	0	0	1	0	0	0	0	2	0	0	1	0	1	0	0
Q	0	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0

TEXT-TABLE VIII. TRANSITION PROBABILITY MATRIX

Good Hope

	A	B	C	F	G	I	J	K	L	M	N	O	P	Q
A	0.00	0.29	0.07	0.25	0.00	0.07	0.00	0.00	0.00	0.11	0.11	0.00	0.04	0.07
B	0.67	0.00	0.17	0.08	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
C	0.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.29	0.04	0.00	0.00	0.04	0.08	0.00	0.00	0.00	0.33	0.04	0.04	0.04	0.08
G	0.00	0.25	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00
I	0.25	0.00	0.00	0.50	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.60	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.20	0.00	0.60	0.00	0.20	0.00	0.00	0.00	0.00	0.00
L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.31	0.06	0.06	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00
N	0.25	0.00	0.00	0.17	0.17	0.00	0.17	0.00	0.00	0.00	0.08	0.00	0.08	0.08
O	0.00	0.00	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
P	0.20	0.20	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.00	0.00
Q	0.20	0.00	0.00	0.40	0.00	0.00	0.00	0.20	0.00	0.00	0.20	0.00	0.00	0.00

Clear Hill

	A	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.00	0.00	0.22	0.11	0.22	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
C	0.00	0.00	0.11	0.33	0.00	0.06	0.00	0.00	0.00	0.00	0.11	0.00	0.22	0.06	0.11
D	0.06	0.17	0.00	0.33	0.00	0.06	0.00	0.00	0.00	0.00	0.06	0.00	0.22	0.06	0.06
E	0.10	0.23	0.06	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.29	0.00	0.13	0.06	0.10
F	0.50	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.22	0.11	0.11	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.22	0.11	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.67	0.00	0.00	0.00	0.00	0.00	0.00
J	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.08	0.00	0.00	0.00	0.15	0.08	0.00	0.00	0.15	0.00	0.08	0.38	0.00	0.08
L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.07	0.00	0.29	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O	0.03	0.09	0.06	0.11	0.00	0.11	0.03	0.03	0.11	0.00	0.03	0.00	0.00	0.14	0.26
P	0.00	0.11	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.22	0.00	0.22
Q	0.00	0.00	0.21	0.11	0.00	0.00	0.00	0.00	0.05	0.00	0.05	0.00	0.42	0.16	0.00

Mountain Creek Bridge

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	0.00	0.80	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.24	0.00	0.24	0.05	0.05	0.00	0.00	0.00	0.10	0.14	0.00	0.05	0.10	0.00	0.05
D	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.18	0.09	0.00	0.00	0.00	0.18	0.00	0.09
E	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.25	0.00	0.00	0.25
F	0.11	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00
G	0.00	0.33	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00
J	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.20	0.00
K	0.00	0.25	0.00	0.00	0.13	0.13	0.00	0.00	0.13	0.00	0.13	0.13	0.00	0.00	0.13
L	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
M	0.00	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
N	0.00	0.40	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
O	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P	0.00	0.40	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00

Taemas Bridge

	A	B	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.00	0.00	0.10	0.05	0.20	0.20	0.05	0.00	0.05	0.00	0.00	0.05	0.30	0.00	0.00	0.00
B	0.13	0.00	0.13	0.00	0.13	0.13	0.13	0.00	0.00	0.00	0.00	0.25	0.00	0.13	0.00	0.00
C	0.00	0.06	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.18	0.18	0.29	0.12	0.06
D	0.29	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.43	0.00	0.00
E	0.12	0.04	0.04	0.08	0.00	0.15	0.00	0.00	0.12	0.15	0.00	0.08	0.00	0.23	0.00	0.00
F	0.26	0.00	0.09	0.04	0.09	0.00	0.00	0.00	0.13	0.00	0.00	0.04	0.17	0.13	0.00	0.04
G	0.00	0.14	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.29	0.14	0.00	0.14
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.08	0.08	0.17	0.17	0.00
K	0.00	0.00	0.00	0.00	0.07	0.00	0.07	0.00	0.07	0.00	0.13	0.00	0.27	0.40	0.00	0.00
L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.16	0.00	0.16	0.05	0.21	0.11	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.21	0.00	0.00
N	0.12	0.08	0.12	0.00	0.00	0.19	0.00	0.00	0.00	0.15	0.00	0.15	0.00	0.19	0.00	0.00
O	0.09	0.06	0.09	0.00	0.17	0.06	0.09	0.03	0.06	0.11	0.00	0.06	0.11	0.00	0.03	0.06
P	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.20	0.00	0.20	0.00	0.00
Q	0.00	0.00	0.25	0.00	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00

TEXT-TABLE IX. INDEPENDENT TRIALS MATRIX

Good Hope

	A	B	C	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	0.120	0.040	0.240	0.040	0.040	0.050	0.050	0.010	0.160	0.120	0.030	0.050	0.050
B	0.241	0.000	0.034	0.207	0.034	0.034	0.043	0.043	0.009	0.138	0.103	0.026	0.043	0.043
C	0.226	0.097	0.000	0.194	0.032	0.032	0.040	0.040	0.008	0.129	0.097	0.024	0.040	0.040
F	0.269	0.115	0.038	0.000	0.038	0.038	0.048	0.048	0.010	0.154	0.115	0.029	0.048	0.048
G	0.226	0.097	0.032	0.194	0.000	0.032	0.040	0.040	0.008	0.129	0.097	0.024	0.040	0.040
I	0.226	0.097	0.032	0.194	0.032	0.000	0.040	0.040	0.008	0.129	0.097	0.024	0.040	0.040
J	0.228	0.098	0.033	0.195	0.033	0.033	0.000	0.041	0.008	0.130	0.098	0.024	0.041	0.041
K	0.229	0.098	0.033	0.195	0.033	0.033	0.041	0.000	0.008	0.130	0.098	0.024	0.041	0.041
L	0.220	0.094	0.031	0.189	0.031	0.031	0.039	0.039	0.000	0.126	0.094	0.024	0.039	0.039
M	0.250	0.107	0.036	0.214	0.036	0.036	0.045	0.045	0.009	0.000	0.107	0.027	0.045	0.045
N	0.241	0.103	0.034	0.207	0.034	0.034	0.043	0.043	0.009	0.138	0.000	0.026	0.043	0.043
O	0.224	0.096	0.032	0.192	0.032	0.032	0.040	0.040	0.008	0.128	0.096	0.000	0.040	0.040
P	0.228	0.098	0.033	0.195	0.033	0.033	0.041	0.041	0.008	0.130	0.098	0.024	0.000	0.041
Q	0.228	0.098	0.033	0.195	0.033	0.033	0.041	0.041	0.008	0.130	0.098	0.024	0.041	0.000

Clear Hill

	A	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	0.103	0.103	0.177	0.011	0.051	0.017	0.011	0.074	0.011	0.080	0.000	0.200	0.051	0.109
C	0.054	0.000	0.108	0.187	0.012	0.054	0.018	0.012	0.078	0.012	0.084	0.000	0.211	0.054	0.114
D	0.054	0.108	0.000	0.187	0.012	0.054	0.018	0.012	0.078	0.012	0.084	0.000	0.211	0.054	0.114
E	0.059	0.118	0.118	0.000	0.013	0.059	0.020	0.013	0.085	0.013	0.092	0.000	0.229	0.059	0.124
F	0.049	0.099	0.099	0.170	0.000	0.049	0.016	0.011	0.071	0.011	0.077	0.000	0.192	0.049	0.104
G	0.051	0.103	0.103	0.177	0.011	0.000	0.017	0.011	0.074	0.011	0.080	0.000	0.200	0.051	0.109
I	0.050	0.099	0.099	0.171	0.011	0.050	0.000	0.011	0.072	0.011	0.077	0.000	0.193	0.050	0.105
J	0.049	0.099	0.099	0.170	0.011	0.049	0.016	0.000	0.071	0.011	0.077	0.000	0.192	0.049	0.104
K	0.053	0.105	0.105	0.181	0.012	0.053	0.018	0.012	0.000	0.012	0.082	0.000	0.205	0.053	0.111
L	0.049	0.099	0.099	0.170	0.011	0.049	0.016	0.011	0.071	0.000	0.077	0.000	0.192	0.049	0.104
M	0.053	0.106	0.106	0.182	0.012	0.053	0.018	0.012	0.076	0.012	0.000	0.000	0.206	0.053	0.112
N	0.049	0.098	0.098	0.168	0.011	0.049	0.016	0.011	0.071	0.011	0.076	0.000	0.190	0.049	0.103
O	0.060	0.121	0.121	0.208	0.013	0.060	0.020	0.013	0.087	0.013	0.094	0.000	0.000	0.060	0.128
P	0.051	0.103	0.103	0.177	0.011	0.051	0.017	0.011	0.074	0.011	0.080	0.000	0.200	0.000	0.109
Q	0.055	0.109	0.109	0.188	0.012	0.055	0.018	0.012	0.079	0.012	0.085	0.000	0.212	0.055	0.000

Mountain Creek Bridge

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	0.000	0.256	0.134	0.049	0.110	0.037	0.024	0.024	0.061	0.098	0.037	0.037	0.061	0.012	0.061
C	0.076	0.000	0.167	0.061	0.136	0.045	0.030	0.030	0.076	0.121	0.045	0.045	0.076	0.015	0.076
D	0.066	0.276	0.000	0.053	0.118	0.039	0.026	0.026	0.066	0.105	0.039	0.039	0.066	0.013	0.066
E	0.060	0.253	0.133	0.000	0.108	0.036	0.024	0.024	0.060	0.096	0.036	0.036	0.060	0.012	0.060
F	0.064	0.269	0.141	0.051	0.000	0.038	0.026	0.026	0.064	0.103	0.038	0.038	0.064	0.013	0.064
G	0.060	0.250	0.131	0.048	0.107	0.000	0.024	0.024	0.060	0.095	0.036	0.036	0.060	0.012	0.060
H	0.059	0.247	0.129	0.047	0.106	0.035	0.000	0.024	0.059	0.094	0.035	0.035	0.059	0.012	0.059
I	0.059	0.247	0.129	0.047	0.106	0.035	0.024	0.000	0.059	0.094	0.035	0.035	0.059	0.012	0.059
J	0.061	0.256	0.134	0.049	0.110	0.037	0.024	0.024	0.000	0.098	0.037	0.037	0.061	0.012	0.061
K	0.063	0.266	0.139	0.051	0.114	0.038	0.025	0.025	0.063	0.000	0.038	0.038	0.063	0.013	0.063
L	0.060	0.250	0.131	0.048	0.107	0.036	0.024	0.024	0.060	0.095	0.000	0.036	0.060	0.012	0.060
M	0.060	0.250	0.131	0.048	0.107	0.036	0.024	0.024	0.060	0.095	0.036	0.000	0.060	0.012	0.060
N	0.061	0.256	0.134	0.049	0.110	0.037	0.024	0.024	0.061	0.098	0.037	0.037	0.000	0.012	0.061
O	0.058	0.244	0.128	0.047	0.105	0.035	0.023	0.023	0.058	0.093	0.035	0.035	0.058	0.000	0.058
P	0.061	0.256	0.134	0.049	0.110	0.037	0.024	0.024	0.061	0.098	0.037	0.037	0.061	0.012	0.000

Taemas Bridge

	A	B	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	0.038	0.082	0.034	0.125	0.111	0.034	0.010	0.058	0.072	0.010	0.091	0.125	0.168	0.024	0.819
B	0.091	0.000	0.077	0.032	0.118	0.105	0.032	0.009	0.055	0.068	0.009	0.086	0.118	0.159	0.023	0.018
C	0.095	0.038	0.000	0.033	0.123	0.109	0.033	0.009	0.057	0.071	0.009	0.090	0.123	0.166	0.024	0.019
D	0.090	0.036	0.077	0.000	0.118	0.104	0.032	0.009	0.054	0.068	0.009	0.086	0.118	0.158	0.023	0.018
E	0.099	0.040	0.084	0.035	0.000	0.114	0.035	0.010	0.059	0.074	0.010	0.094	0.129	0.173	0.025	0.020
F	0.098	0.039	0.083	0.034	0.127	0.000	0.034	0.010	0.059	0.073	0.010	0.093	0.127	0.171	0.024	0.020
G	0.090	0.036	0.077	0.032	0.118	0.104	0.000	0.009	0.054	0.068	0.009	0.086	0.118	0.158	0.023	0.018
I	0.088	0.035	0.075	0.031	0.115	0.102	0.031	0.000	0.053	0.066	0.009	0.084	0.115	0.155	0.022	0.018
J	0.093	0.037	0.079	0.032	0.120	0.106	0.032	0.009	0.000	0.069	0.009	0.088	0.120	0.162	0.023	0.019
K	0.094	0.038	0.080	0.033	0.122	0.108	0.033	0.009	0.056	0.000	0.009	0.089	0.122	0.164	0.023	0.019
L	0.088	0.035	0.075	0.031	0.115	0.102	0.031	0.009	0.053	0.066	0.000	0.084	0.115	0.155	0.022	0.018
M	0.096	0.038	0.081	0.033	0.124	0.110	0.033	0.010	0.057	0.072	0.010	0.000	0.124	0.167	0.024	0.019
N	0.099	0.040	0.084	0.035	0.129	0.114	0.035	0.010	0.059	0.074	0.010	0.094	0.000	0.173	0.025	0.020
O	0.104	0.041	0.088	0.036	0.135	0.119	0.036	0.010	0.062	0.078	0.010	0.098	0.135	0.000	0.026	0.021
P	0.090	0.036	0.076	0.031	0.117	0.103	0.031	0.009	0.054	0.067	0.009	0.085	0.117	0.157	0.000	0.018
Q	0.089	0.036	0.076	0.031	0.116	0.103	0.031	0.009	0.054	0.067	0.009	0.085	0.116	0.156	0.022	0.000

TEXT-TABLE X. DIFFERENCE MATRIX

Good Hope

	A	B	C	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	0.166	0.031	0.010	-0.040	0.031	-0.050	-0.050	-0.010	-0.053	-0.013	-0.030	-0.014	0.021
B	0.425	0.000	0.132	-0.124	-0.034	-0.034	-0.043	-0.043	-0.009	-0.055	-0.103	-0.026	-0.043	-0.043
C	0.024	0.653	0.000	-0.194	-0.032	-0.032	-0.040	-0.040	-0.008	-0.129	-0.097	-0.024	-0.040	-0.040
F	0.022	-0.074	-0.038	0.000	0.003	0.045	-0.048	-0.048	-0.010	0.179	-0.074	0.013	-0.006	0.035
G	-0.226	0.153	-0.032	0.056	0.000	-0.032	-0.040	-0.040	-0.008	-0.129	0.403	-0.024	-0.040	-0.040
I	0.024	-0.097	-0.032	0.306	-0.032	0.000	-0.040	0.210	-0.008	-0.129	-0.097	-0.024	-0.040	-0.040
J	-0.228	-0.098	-0.033	-0.195	-0.033	-0.033	0.000	0,359	-0.008	-0.130	0.502	-0.024	-0.041	-0.041
K	-0.228	-0.098	-0.033	-0.195	0.167	-0.033	0.559	0.000	0.192	-0.130	-0.098	-0.024	-0.041	-0.041
L	-0.220	-0.094	-0.031	-0.189	-0.031	-0.031	-0.039	0.961	0.000	-0.126	-0.094	-0.024	-0.039	-0.039
M	0.063	-0.045	0.027	0.286	-0.036	-0.036	-0.045	-0.045	-0.009	0.000	-0.107	-0.027	0.018	-0.045
N	0.009	-0.103	-0.034	-0.040	0.132	-0.034	0.124	-0.043	-0.009	-0.138	0.083	-0.026	0.040	0.040
O	-0.224	-0.096	0.301	0.141	-0.032	-0.032	-0.040	-0.040	-0.008	-0.128	-0.096	0.000	0.293	-0.040
P	-0.028	0.102	-0.033	0.005	-0.033	-0.033	-0.041	-0.041	-0.008	-0.130	0.102	0.176	0.000	-0.041
Q	-0.028	-0.098	-0.033	0.205	-0.033	-0.033	-0.041	0.159	-0.008	-0.130	0.102	-0.024	-0.041	0.000

Clear Hill

	A	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	-0.103	0.119	-0.066	0.211	0.060	-0.017	-0.011	-0.074	-0.011	-0.080	0.000	0.133	-0.051	-0.109
C	-0.054	0.000	0.003	0.147	-0.012	0.001	-0.018	-0.012	-0.078	-0.012	0.027	0.000	0.011	0.001	-0.003
D	0.001	0.058	0.000	0.147	-0.012	0.001	-0.018	-0.012	-0.078	-0.012	-0.029	0.000	0.011	0.001	-0.059
E	0.038	0.108	-0.053	0.000	-0.013	-0.059	0.013	-0.013	-0.085	-0.013	0.199	0.000	-0.100	0.006	-0.027
F	0.451	-0.099	-0.099	-0.170	0.000	0.451	-0.016	-0.011	-0.071	-0.011	-0.077	0.000	-0.192	-0.049	-0.104
G	0.171	0.008	0.008	-0.177	-0.011	0.000	-0.017	-0.011	0.148	-0.011	-0.080	0.000	0.022	0.060	-0.109
I	-0.050	-0.099	-0.099	-0.171	-0.011	-0.050	0.000	0.322	0.595	-0.011	-0.077	0.000	-0.193	-0.050	-0.105
J	-0.049	-0.099	-0.099	0.330	-0.011	-0.049	-0.016	0.000	0.429	-0.011	-0.077	0.000	-0.192	-0.049	-0.104
K	-0.053	-0.028	-0.105	-0.181	-0.012	0.101	0.059	-0.012	0.000	0.142	-0.082	0.077	0.180	-0.053	-0.034
L	-0.049	-0.099	-0.099	-0.170	-0.011	-0.049	-0.016	-0.011	0.929	0.000	-0.077	0.000	-0.192	-0.049	-0.104
M	0.018	-0.106	0.180	0.318	-0.012	-0.053	-0.018	-0.012	-0.076	-0.012	0.000	0.000	-0.206	-0.053	0.031
N	-0.049	-0.098	-0.098	-0.168	-0.011	-0.049	-0.016	-0.011	-0.071	-0.011	-0.076	0.000	-0.190	-0.049	-0.103
O	-0.032	-0.035	-0.064	-0.094	-0.013	0.054	0.008	0.015	0.027	-0.013	-0.065	0.000	0.000	0.082	0.130
P	-0.051	0.008	0.230	-0.177	-0.011	-0.051	-0.017	-0.011	-0.074	-0.011	0.031	0.000	0.022	0.000	0.114
Q	-0.055	-0.109	0.101	-0.083	-0.012	-0.055	-0.018	-0.012	-0.026	-0.012	-0.032	0.000	0.209	0.103	0.000

Mountain Creek Bridge

	A	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	0.000	0.544	-0.134	-0.049	0.090	-0.037	-0.024	-0.024	-0.061	-0.098	-0.037	-0.037	-0.061	-0.012	-0.061
C	0.162	0.000	0.071	-0.013	0.089	-0.045	-0.030	-0.030	0.019	0.022	-0.045	0.002	0.019	-0.015	-0.028
D	-0.066	0.178	0.000	-0.053	-0.118	-0.039	-0.026	0.156	0.025	-0.105	-0.039	-0.039	0.116	-0.013	0.025
E	-0.060	-0.003	-0.133	0.000	-0.108	-0.036	-0.024	-0.024	-0.060	0.154	-0.036	0.214	-0.060	-0.012	0.190
F	0.047	0.509	-0.141	-0.051	0.000	-0.038	-0.026	-0.026	-0.064	0.009	-0.038	-0.038	-0.064	-0.013	-0.064
G	-0.060	0.083	-0.131	-0.048	-0.107	0.000	0.643	-0.024	-0.060	-0.095	-0.036	-0.036	-0.060	-0.012	-0.060
H	-0.059	-0.247	-0.129	-0.047	-0.106	0.965	0.000	-0.024	-0.059	-0.094	-0.035	-0.035	-0.059	-0.012	-0.059
I	-0.059	-0.247	0.371	-0.047	-0.106	-0.035	-0.024	0.000	0.441	-0.094	-0.035	-0.035	-0.059	-0.012	-0.059
J	-0.061	0.344	-0.134	-0.049	-0.110	-0.037	-0.024	-0.024	0.000	0.102	-0.037	-0.037	-0.061	0.188	-0.061
K	-0.063	-0.016	-0.139	-0.051	0.011	0.087	-0.025	-0.025	0.062	0.000	0.087	0.087	-0.063	-0.013	0.062
L	-0.060	0.417	-0.131	-0.048	-0.107	-0.036	-0.024	-0.024	-0.060	0.238	0.000	-0.036	-0.060	-0.012	-0.060
M	-0.060	0.083	0.202	-0.048	-0.107	-0.036	-0.024	-0.024	-0.060	0.238	-0.036	0.000	-0.060	-0.012	-0.060
N	-0.061	0.144	0.266	-0.049	-0.110	-0.037	-0.024	-0.024	-0.061	-0.098	-0.-37	-0.037	0.000	-0.012	0.139
O	-0.058	-0.244	-0.128	0.953	-0.105	-0.035	-0.023	-0.023	-0.058	-0.093	-0.035	-0.035	-0.058	0.000	-0.058
P	-0.061	0.144	0.066	0.151	-0.110	-0.037	-0.024	-0.024	-0.061	0.102	-0.037	-0.037	-0.061	-0.012	0.000

Taemas Bridge

	A	B	C	D	E	F	G	I	J	K	L	M	N	O	P	Q
A	0.000	-0.038	0.018	0.016	0.075	0.089	0.016	-0.010	-0.008	-0.072	-0.010	-0.041	0.175	-0.168	-0.024	-0.019
B	0.034	0.000	0.048	-0.032	0.007	0.020	0.093	-0.009	-0.055	-0.068	-0.009	0.164	-0.118	-0.034	-0.023	-0.018
C	-0.095	0.021	0.000	-0.033	-0.123	0.009	-0.033	-0.009	-0.057	-0.071	-0.009	0.086	0.053	0.128	0.094	0.040
D	0.195	-0.036	-0.077	0.000	0.025	-0.104	-0.032	-0.009	-0.054	-0.068	-0.009	0.057	-0.118	0.270	-0.023	-0.018
E	0.016	-0.001	-0.046	0.042	0.000	0.040	-0.035	-0.010	0.056	0.080	-0.010	-0.017	-0.129	0.058	-0.025	-0.020
F	0.163	-0.039	0.004	0.009	-0.040	0.000	-0.034	-0.010	0.072	-0.073	-0.010	-0.049	0.047	-0.040	-0.024	0.024
G	-0.090	0.107	-0.077	-0.032	0.025	-0.104	0.000	-0.009	-0.054	0.075	-0.009	-0.086	0.168	-0.016	-0.023	0.125
I	-0.088	-0.035	-0.075	-0.031	-0.115	-0.102	-0.031	0.000	-0.053	-0.066	-0.009	0.916	-0.115	-0.155	-0.022	-0.018
J	-0.093	-0.037	-0.079	-0.032	0.130	0.144	-0.032	-0.009	0.000	-0.069	-0.009	-0.005	-0.037	0.005	0.144	-0.019
K	-0.094	-0.038	-0.080	-0.033	-0.055	-0.108	0.034	-0.009	0.010	0.000	0.124	-0.089	0.145	0.236	-0.023	-0.019
L	-0.088	-0.035	-0.075	-0.031	-0.115	-0.102	-0.031	-0.009	-0.053	0.934	0.000	-0.084	-0.115	-0.155	-0.022	-0.018
M	0.062	-0.038	0.077	0.019	0.086	-0.005	-0.033	0.043	-0.005	-0.072	-0.010	0.000	-0.124	0.043	-0.024	-0.019
N	0.016	0.037	0.031	-0.035	-0.129	0.078	-0.035	-0.010	-0.059	0.080	-0.010	0.060	0.000	0.019	-0.025	-0.020
O	-0.018	0.016	-0.002	-0.036	0.037	-0.062	0.049	0.018	-0.005	0.037	-0.010	-0.041	-0.020	0.000	0.003	0.036
P	-0.090	-0.036	-0.076	0.169	-0.117	-0.103	-0.031	-0.009	0.346	-0.067	-0.009	0.115	-0.117	0.043	0.000	-0.018
Q	-0.089	-0.036	0.174	-0.031	0.134	0.147	-0.031	-0.009	-0.054	-0.067	-0.009	-0.085	0.134	-0.156	-0.022	0.000

<u>Spatial relationships</u>

From the difference matrix, by starting with the first rock type and systematically following the path of highest positive values (Gingerich, 1967, p.331; Lumsden, 1971, p.457), tree diagrams (Allen, 1970, p.305) may be constructed.[1] These not only emphasize any cyclicity that may be present, but also provide clues as to possible spatial arrangements of the various rock types during the deposition of the Cavan Limestone.

Due to the large number of rock types, it was found more practical to prepare two sets of tree diagrams for each type section. One set takes in the 12 carbonate rock types, the other the terrigenous rock types plus any carbonate types they are associated with. In effect, the first set shows the interrelationships between the carbonate rocks, the second set, the relationship between the terrigenous and carbonate rocks. It was reasoned that by combining the two, a fairly accurate depositional model would emerge. However, due to the fact that the geology of the terrigenous beds is not well known, since they were only studied summarily, it was found more meaningful to use the carbonate-carbonate diagrams as the basis for the model, and to use the terrigenous-carbonate diagrams to show how the pattern was modified by the presence of an appreciable amount of terrigenous debris. It was also necessary in several cases to assume the existence of more than one major area of deposition for a particular rock type.

By using an overlay of each tree diagram showing the carbonate interrelationships (Fig.5), a composite diagram may be constructed, the spatial relationships of which take on an added meaning, when the environments inferred from

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[1]Except in the case of the composite tree diagram, linkages with values between 0.150 and 0.30 are shown with broken lines, those greater than 0.30 with solid lines.

Chapter 3 are depicted on it (Fig.6). The most ambiguous situations regard the skeletal micritic wackestone, microspar wackestone, and skel-algal packstone rock groups. However, the tree diagrams suggest that the first group may have formed as echinoderm banks which inhibited circulation, and provided a back-reef type of environment in which the micritic mudstones accumulated. The microspar wackestones seem to be predominantly intertidal, since the rocks are often associated with algal limestones and calcretes. The skel-algal packstones, because of their close association with skeletal rocks and mollusk-gastropod wackestones, probably formed in a more-or-less open shallow subtidal environment, where algae were particularly abundant. At times they may have formed echinoderm banks, to the sheltered side of which the mollusk-gastropod wackestones were deposited.

Bearing these interpretations in mind, Fig.7 can be constructed which shows the relationship between the composite tree diagram and the major environments inferred for the Cavan Limestone. This forms the basis for the depositional model.

The modifications brought about by the presence of terrigenous detritus can be studied by compiling a composite tree diagram (Fig.8), using the individual terrigenous-carbonate diagrams (Fig.9), and by depicting on this the major carbonate environments. Alternatively, it can be examined by studying Table XI[1], which shows the frequency of occurrence of carbonate beds with terrigenous beds. Clearly, most of the terrigenous rocks are associated with intertidal and subtidal rocks. The lagoonal rocks are relatively free of terrigenous beds except for the micritic mudstone, which is, not surprisingly, associated with clay. Any inter-

[1]Based on difference matrix values $\geqslant$ 0.150.

pretations are of necessity very general. However, one feasible theory is that the relationships between the intertidal carbonate rocks were greatly affected by a prograding body of terrigenous material, that periodically transgressed across into the subtidal areas. These periodic incursions may ultimately have accounted for the distinctive nodularity of the fossiliferous beds. (See p.92.) Presumably, the lagoonal areas were not inundated by these incursions. By analogy with the Gladstone embayment in Shark Bay, Western Australia (Davies, p.171, 1970), it is conceivable that this prograding body of terrigenous material was a delta, that eventually overran the carbonate tidal flat, giving rise to the red sandstones and shales of the Majurgong Formation, which immediately overlies the Cavan Limestone. However, this is highly speculative. Nevertheless, for want of a better hypothesis, this idea is incorporated into the construction of the depositional model.

These then are the interpretations and ideas used in the construction of the depositional model.

5.4 DEPOSITIONAL MODEL

Fig.10 represents an attempt at the environmental reconstruction of the Cavan Limestone. It depicts three main areas of deposition. These are supratidal, intertidal and shallow subtidal, the latter being lagoonal and biostromal or bank-like in parts.

Supratidal Environment

This occurred immediately above the mean high tide mark. Occasional storms or unusually high tides inundated large areas and deposited carbonate muds, occasionally containing appreciable quantities of gastropod intraclasts and rarely, some skeletal debris. As the waters receded, in a few localised areas, algal mats may have flourished on the wet substrate. Eventual desiccation of the flats followed with the formation of polygonal mudcracks. Muds below the air-sediment interface slowly dried and shrank, causing some internal shrinkage, and the formation of birdseye structure. No organisms flourished here except for a few burrowing worms or anthropods. On the highest parts of the flats, on exposed or soil-covered areas, calcretes formed.

Intertidal Environment

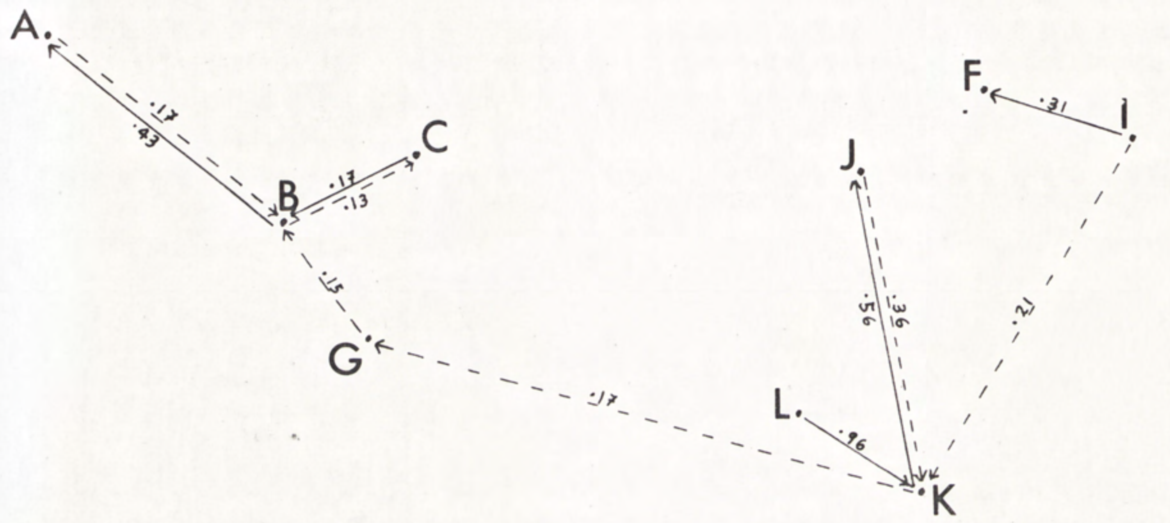
This area was characterised by diurnal exposures to the atmosphere. Except during inundation by high tides or storms, the higher parts of this zone were exposed and dried for long periods and, as a result, underwent desiccation and mudcracking as did the supratidal. Here, some gastropod wackestones were deposited. In contrast, on the lower areas, desiccation was less prevalent, and deposition, reworking and redistribution of sediments was correspondingly more common, because of the greater frequency of flooding. Concentration of storm or tidal energies produced local scouring, resulting in layers of grain-supported intraclast and skeletal debris, being interlaminated with a variety of rock types. Flooding of desiccated muds by storms tore up mudcracked polygons and redeposited them as conglomeratic layers. In such areas, algal mats flourished and served as sediment traps for pelletal carbonate muds. They were closely associated with areas where pelletal packstones and wackestones were forming which, during times of pronounced terrigenous influx, gave way to terrigenous and pelletal wackestones and packstones. Elsewhere isolated patches of microspar wackestones were accumulating. In a general way these sediments became less prevalent towards the supratidal zone, but there was no orderly arrangement of facies, as the area was subjected to frequent influxes of terrigenous material, possibly from a prograding delta.

Subtidal Environment

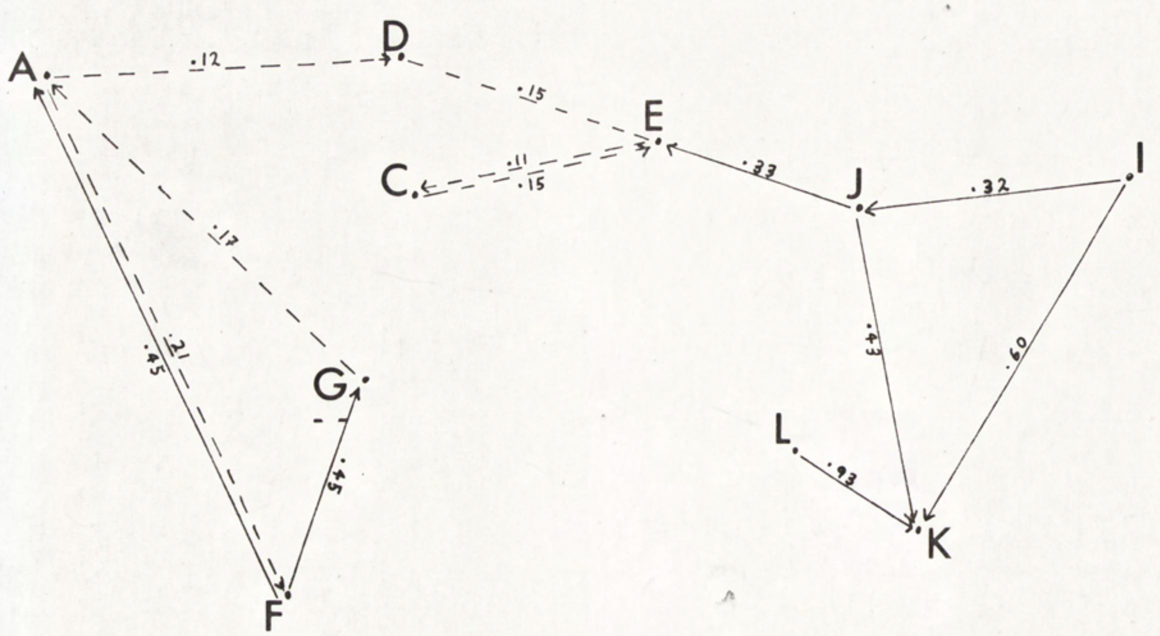
This lay immediately below the mean low-tide mark. Overall, hydrodynamic energy conditions were low and, as a result, micritic or microspar muds accumulated on the sea floor. Nevertheless, generally ecological conditions favoured an abundant and diverse biota. In many areas, Cystiphyllum biostromes and echinoderm banks and meadows flourished, and provided suitable sites on their landward side for the deposition of mollusk-gastropod wackestones and skeletal micritic wackestones respectively. Elsewhere, probably very close to the low-tide mark and in areas where algae were very active, skel-algal sediments were deposited. In the few places of higher energy, sparites formed. Periodically, appreciable quantities of predominantly fine-grained terrigenous detritus inundated these shallow waters, and for long periods the overall pattern of sedimentation,was probably one of alternating deposition of limestone and marl or clay.

TEXT-FIG.5. CARBONATE-CARBONATE TREE DIAGRAMS

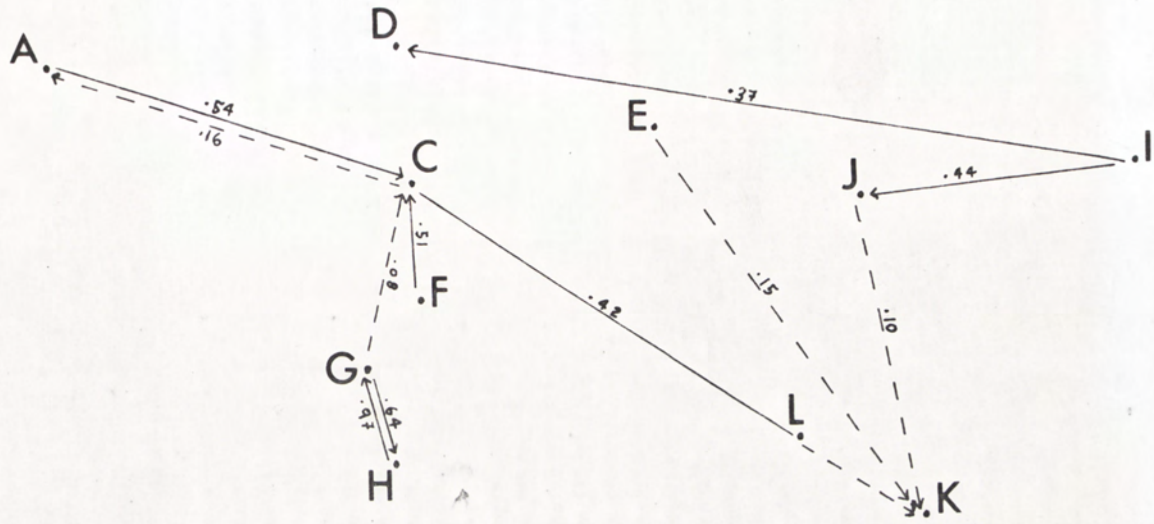
a) GOOD HOPE



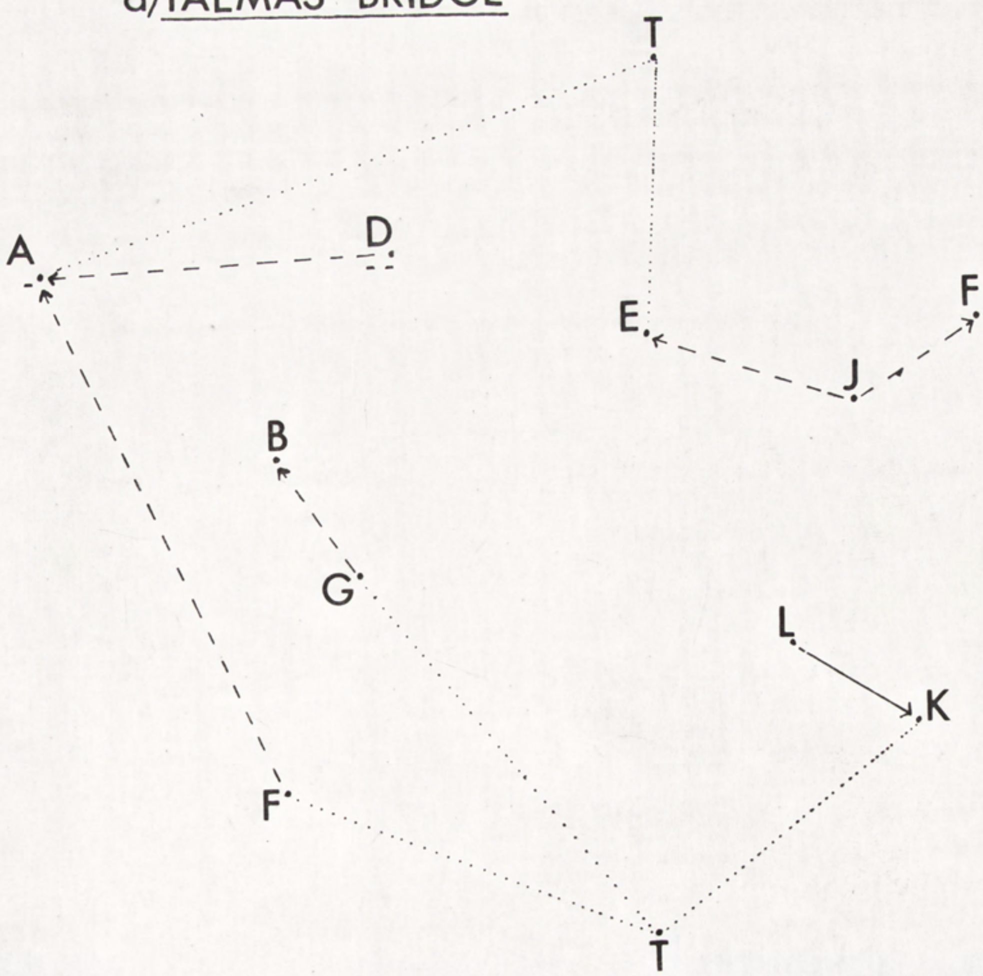
b) CLEAR HILL



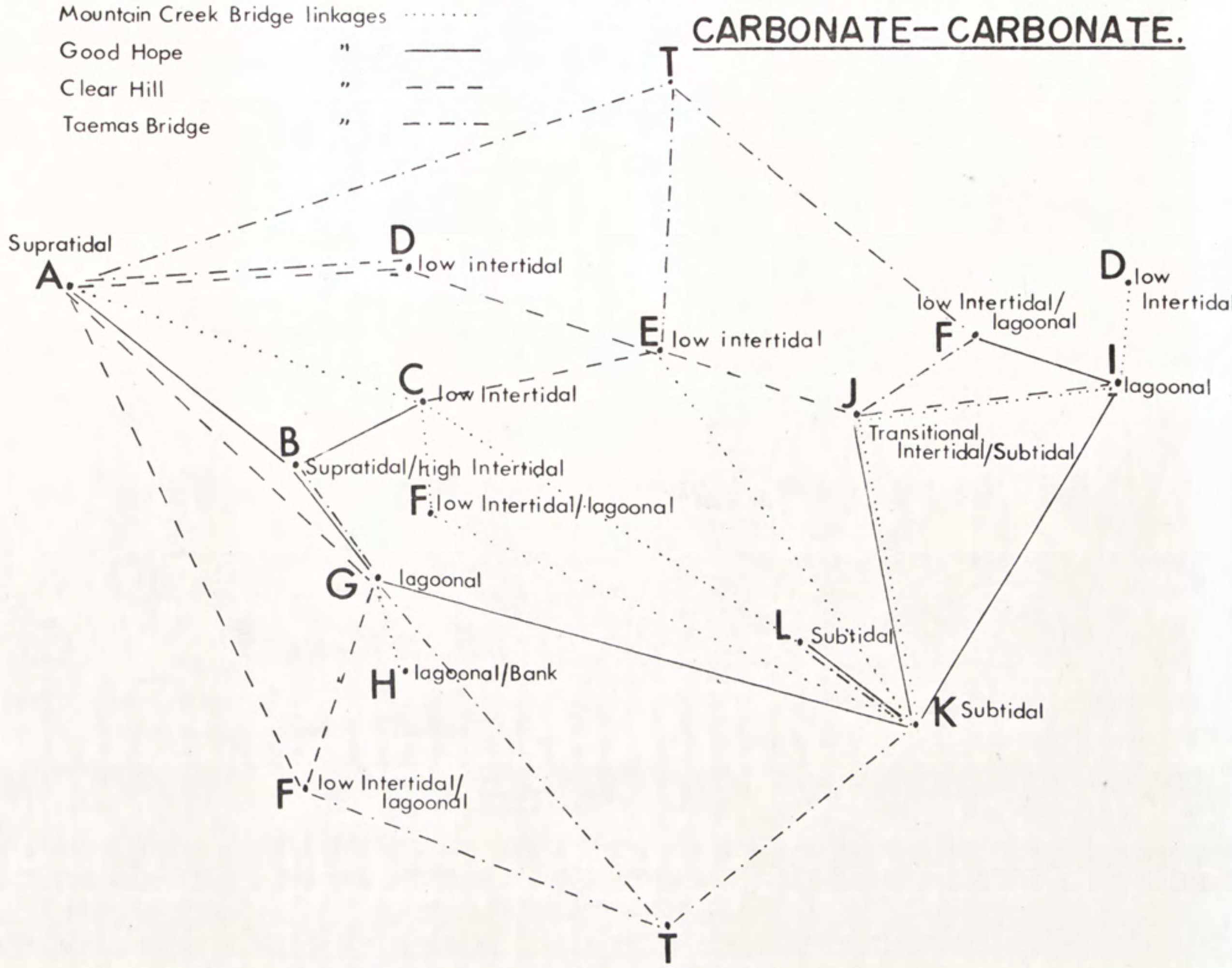
c) MOUNTAIN CREEK BRIDGE



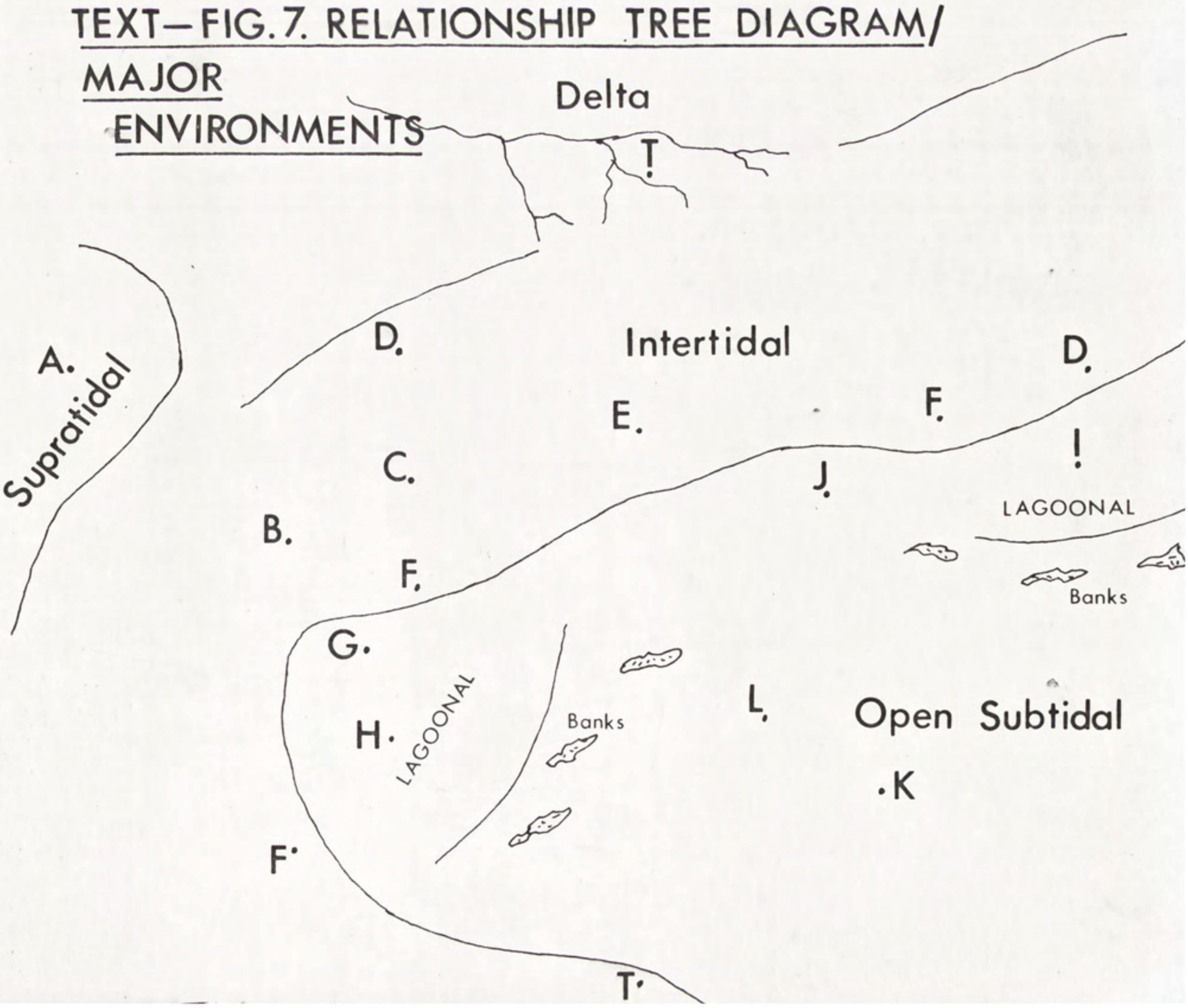
d) TAEMAS BRIDGE



TEXT—FIG. 6. COMPOSITE TREE DIAGRAM, CARBONATE—CARBONATE.

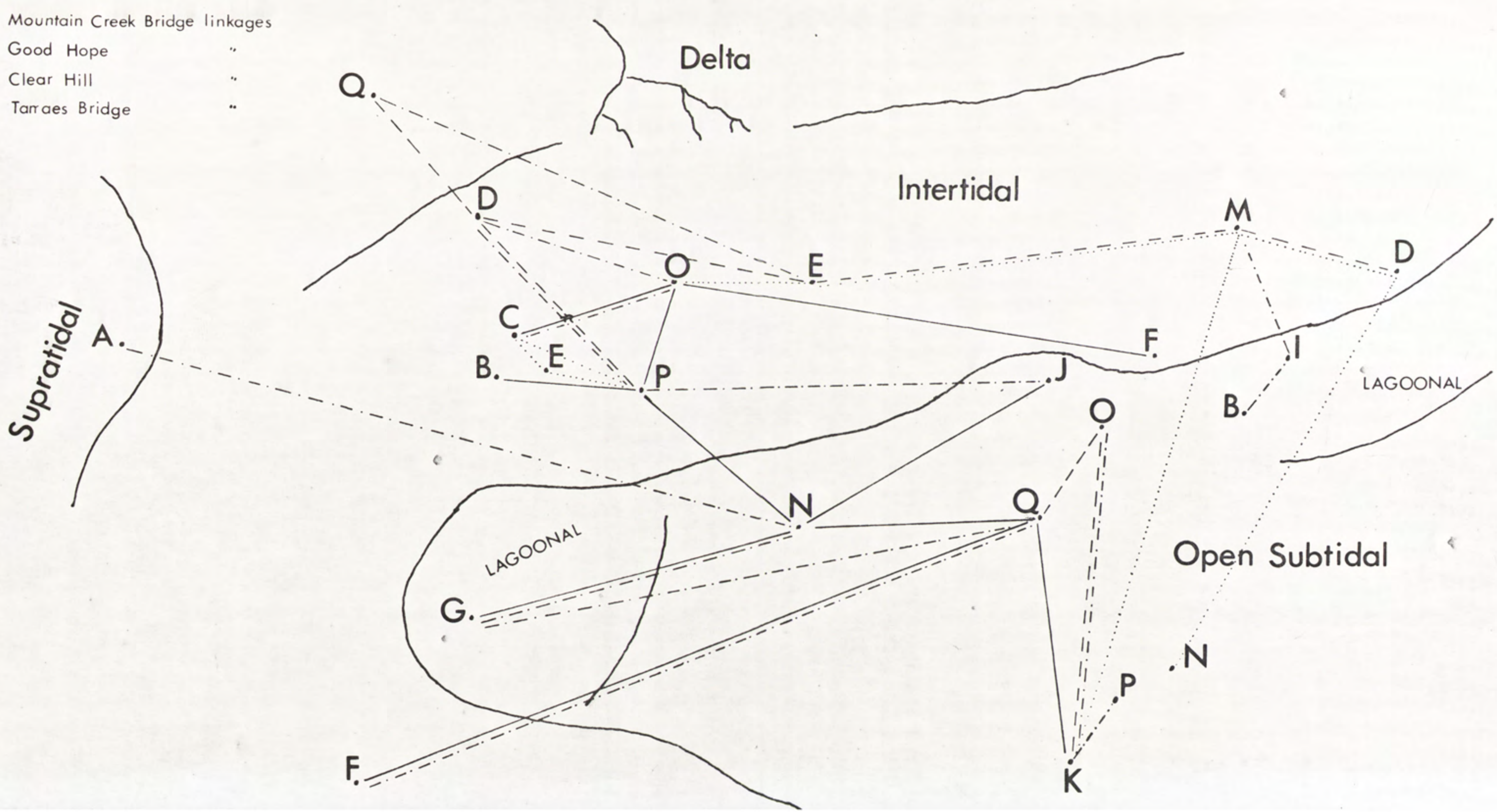


TEXT—FIG. 7. RELATIONSHIP TREE DIAGRAM/ MAJOR ENVIRONMENTS



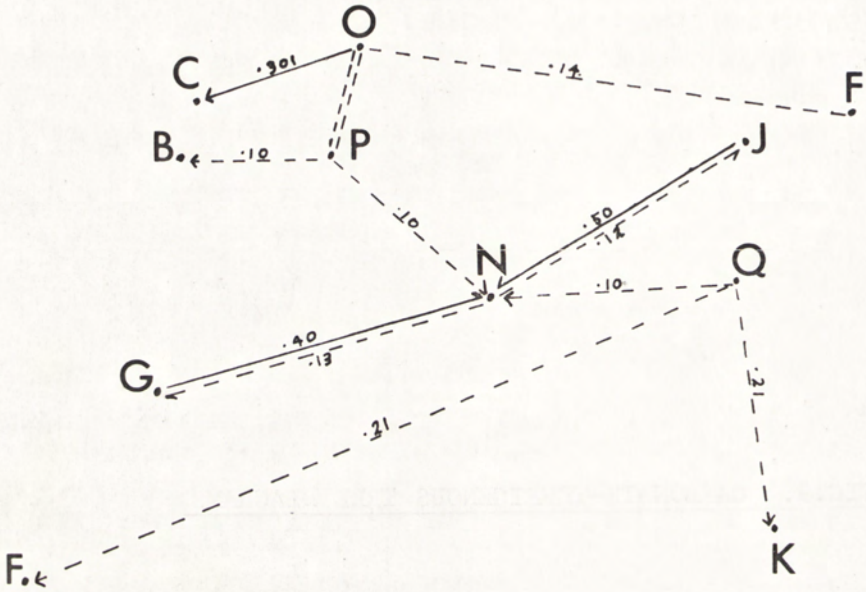
RELATIONSHIP COMPOSITE CARBONATE—TERRIGENOUS TREE DIAGRAM/ MAJOR CARBONATE ENVIRONMENTS

TEXT–FIG. 8.

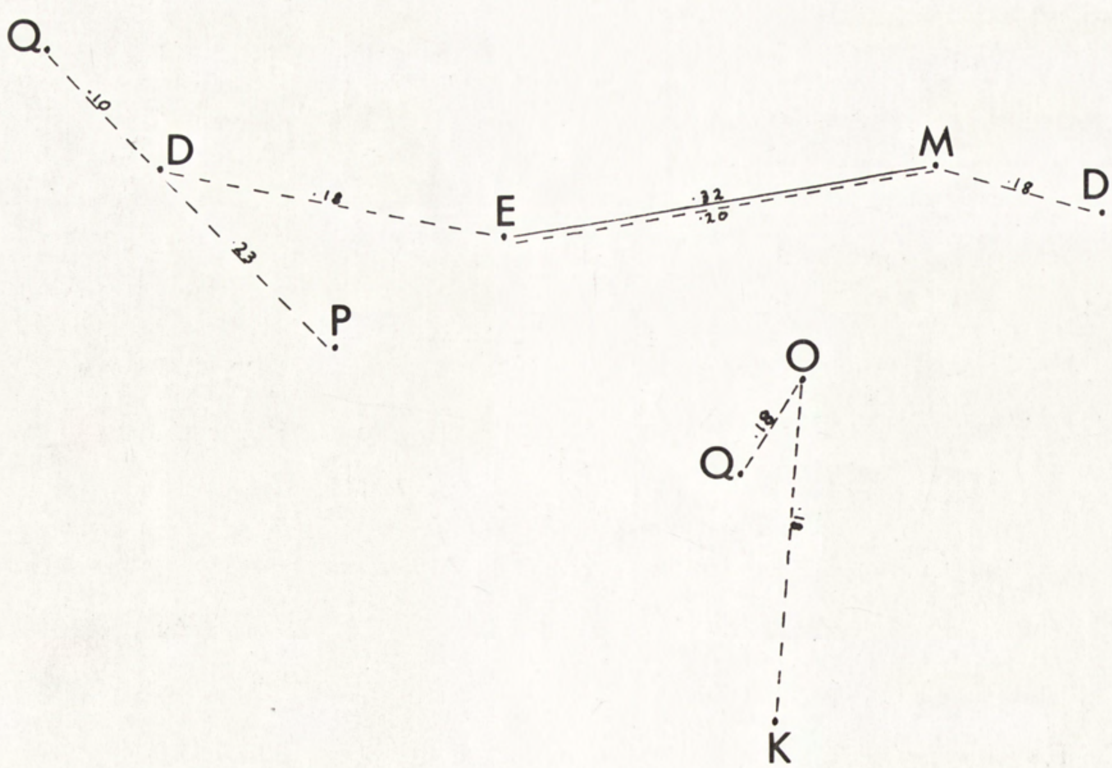


TEXT-FIG.9. CARBONATE-TERRIGENOUS TREE DIAGRAMS

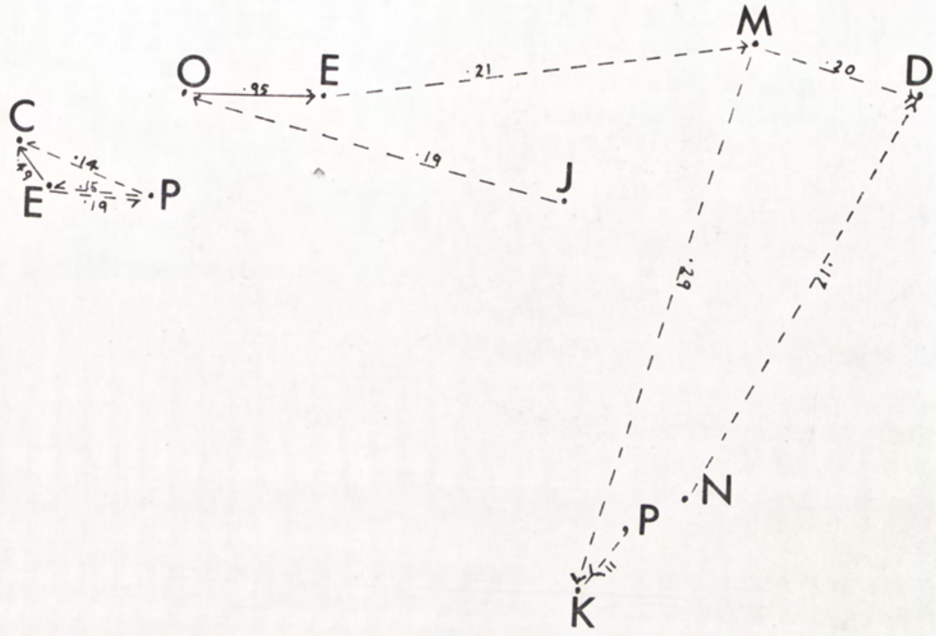
GOOD HOPE



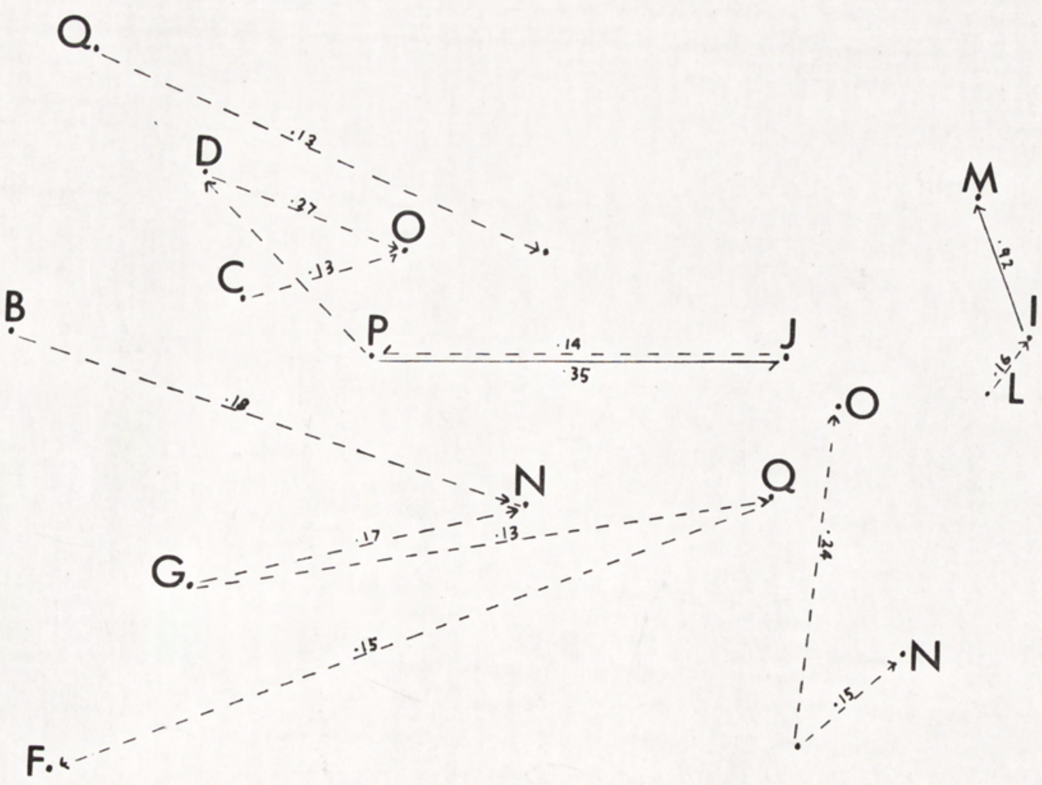
CLEAR HILL



MOUNTAIN CREEK BRIDGE



TAEMAS BRIDGE



TEXT-TABLE XI. FREQUENCY OF OCCURRENCE OF CARBONATE ROCK TYPES WITH TERRIGENOUS ROCKS

	Carbonate rock type	Marl	Clay	Shale	Silt-stone	Sand-stone
SUPRATIDAL	Calcrete		r			
	Gastropod w[1]	r			r	
INTERTIDAL	Algal limestone		r	r	r	r
	Terrigenous & pelletal w & p[2]	c	c	r	c	r
	Pelletal w & p	r		r	c	r
	Microspar w	v.c				c
LAGOONAL	Micritic Mudstone		v.c			r
	Skeletal Micritic w					
	Mollusk-gastropod w	r				
SUBTIDAL	Skel-algal p		c	r	c	
	Skeletal w & p		r	c		r
	Skeletal grainstone					

blank = nil
r = rare
c = common
v.c = very common

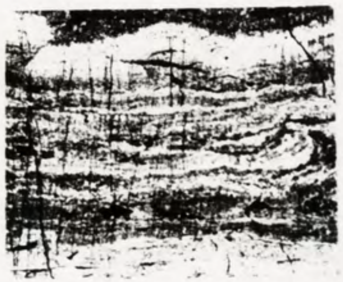
[1]w = wackestone
[2]p = packstone

TEXT FIG. 10. ENVIRONMENTAL RECONSTRUCTION OF THE CAVAN LIMESTONE

ROCK TYPES OF THE CAVAN LIMESTONE

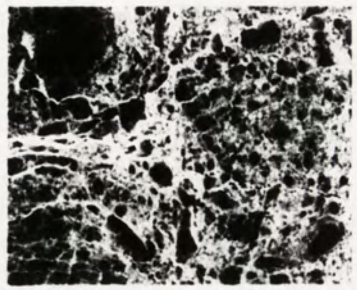
(Acetate Peels, x2)

CALCRETE



A

GASTROPOD W



B

ALGAL LIMESTONE

C

TERRIGENOUS AND PELLETAL W & P

D

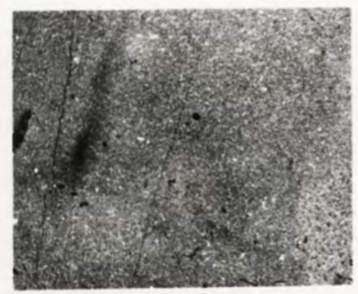
PELLETAL W & P

E

MICROSPAR W

F

MICRITIC MUDSTONE



G

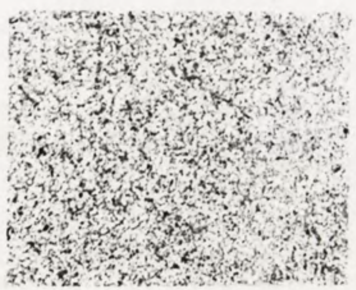
SKELETAL MICRITIC W

H

MOLLUSK-GASTROPOD W

I

SKEL-ALGAL P

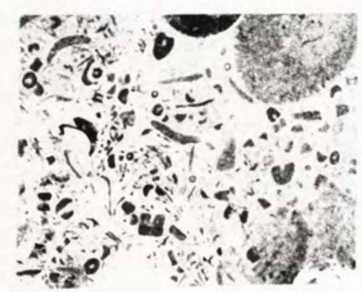


J

SKELETAL W & P

K

SKELETAL GRAINSTONE



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CHAPTER 6

PALAEOGEOGRAPHIC EVOLUTION

6.1 INTRODUCTION

As pointed out in Chapter 1, the Lower Devonian sequence in the Goodradigbee Valley (see Fig.2) bears a striking similarity to that of the Taemas-Cavan area. Reconnaissance studies on the Cavan Limestone in the Goodradigbee area certainly substantiate this. There the sequence is of comparable thickness, is composed of the same rock types, contains the same general fauna and displays similar lateral variations. For all practical purposes, the successions in the two areas are identical. This suggests similar conditions of sedimentation and environment over an appreciable area, and leads naturally into a consideration of the palaeogeography and geological history of the area as a whole.

These considerations require detailed correlations between sections. This was greatly assisted by grading the rock types from 1 to 8 (the values may be thought of as a depositional index), depending on their depositional environment, and by plotting the variation in these against the lithological columns, drawn up for the four type localities (see Logs). They were graded from supratidal to subtidal as:

8, skeletal grainstones and skeletal packstones and wackestones.

7, skel-algal packstones.

6, skeletal micritic wackestones and micritic mudstones.

subtidal

5, mollusk-gastropod wackestones.

4, microspar wackestones.

3, algal limestones, pelletal wackestones and packstones, and terrigenous and pelletal wackestones and packstones.

2, gastropod wackestones.

1, calcrete.

Because of only a sketchy knowledge of the terrigenous rocks, these were all graded as intertidal (3), which undoubtedly most of them are, even though as shown by Fig.8 and Table VI, some of them are subtidal.

The curves, which may be called depositional environment (D.E.) curves, were correlated using various recurring significant features, numbered from 1 to 49. (Calcretes were very helpful in this, although the stratigraphical use of individual calcrete bands is strictly limited.) Portions of the curve are referred to by the locality plus a number. G.H., C.H., M.C. and T.B. refer to Good Hope, Clear Hill, Mountain Creek Bridge and Taemas Bridge respectively.

In the final section of this chapter, the megacyclicity within the Cavan Limestone is stressed.

6.2 PALAEOGEOGRAPHY

Fig.11 shows the palaeogeography of southeast Australia during the Early and Middle Devonian. Most pertinent to this study is the Buchan-Taemas-Molong Platform which was formed during the Bowning Orogeny, when the Condobolin High was partly submerged. Not surprisingly, this platform had considerable relief, and one of the structures initiated on it about this time, occupied the Goodradigbee-Taemas areas.[1] Most probably its major elements were a northeast trending

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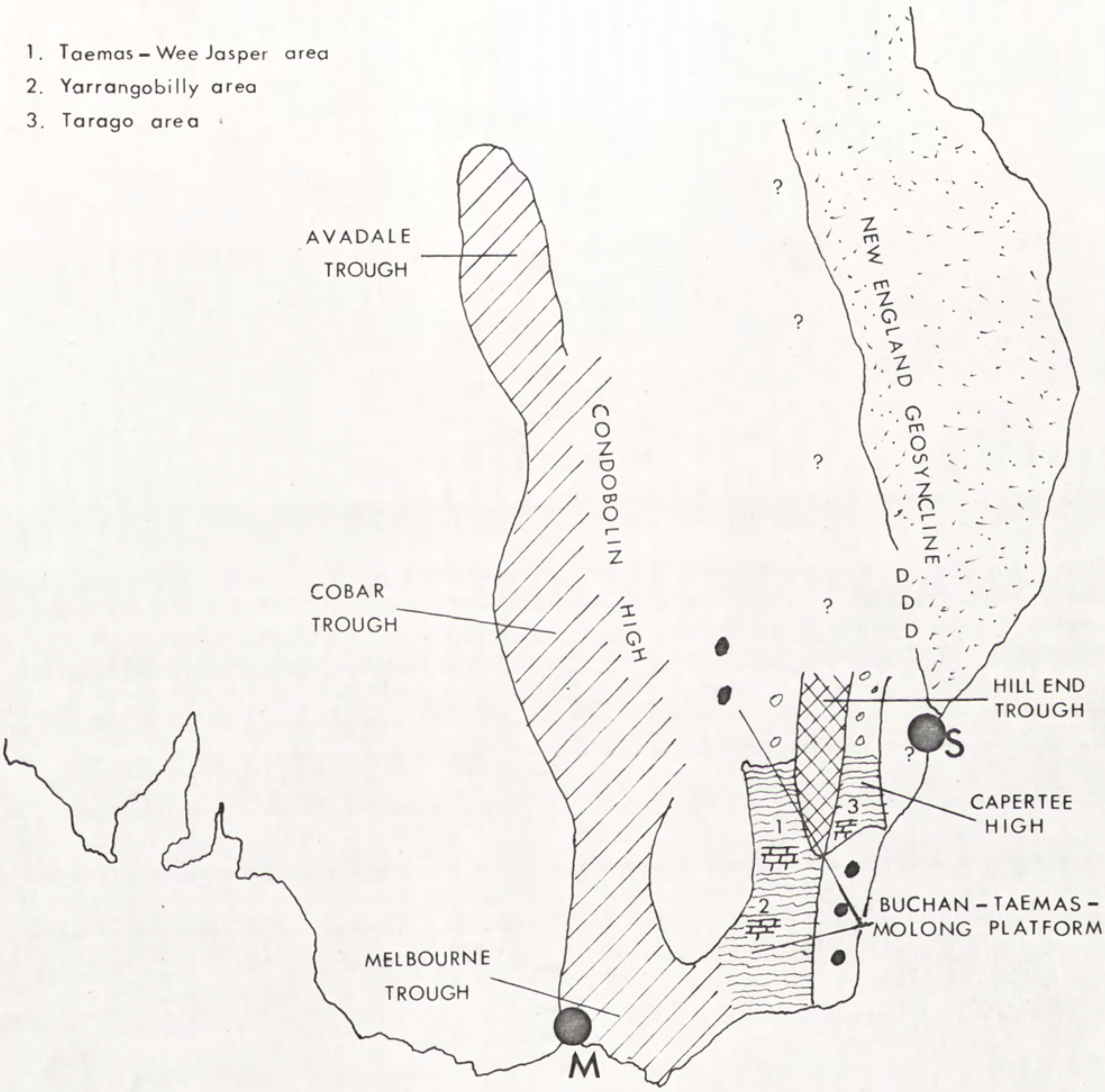
[1] Similar structures probably formed towards the east and towards the south, in what is now the Tarago and Yarrangobilly areas respectively (see Fig.11).

TEXT-FIG. 11.

EARLY AND MIDDLE DEVONIAN PALAEOGEOGRAPHY



areas of shallow water basin sedimentation with Siluro-Devonian conformity; without volcanics

areas of platform sedimentation and volcanics; unconformity at base

areas of shallow water sedimentation and volcanics; apparent conformity at base

areas of trough sedimentation; conformity at base

New England Geosyncline with greywackes, slates and volcanics; coralline limestones "D"

terrestrial volcanics

basin with its depocentre in the vicinity of Narrangullen, and with landmasses, chiefly of acid volcanics, towards the northwest and southeast. Evidence for this comes from three sources.

Isopach maps

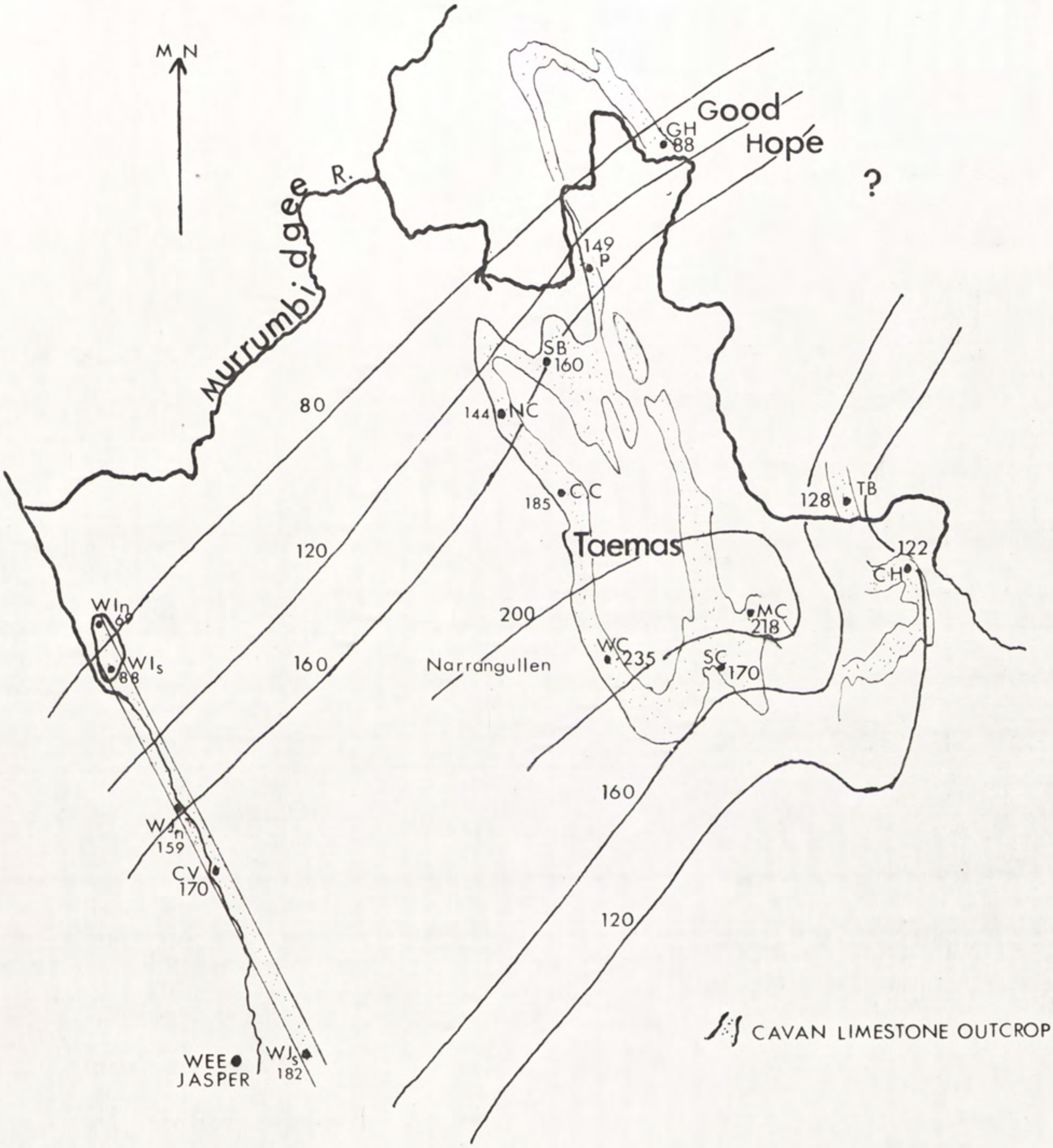
Fig.12 shows the isopach map of the total thickness of the Cavan Limestone. In the Goodradigbee area there is obvious thinning of the succession towards the northwest. At Taemas, the thinning is not so apparent, but generally takes place towards the southeast. That this thinning is stratigraphic as opposed to tectonic, is indicated by the fact that the thickness of the individual members also decreases in these directions. (See Fig.13 where the isopach maps of the Flaggy Limestone member, the Yellow Limestone member, and combined Bluff, Nodular and Micritic Limestone members are shown.)

An interesting feature suggested by the maps is that, geologically, Wee Jasper south is part of the Taemas area. In agreement with this is its relative abundance of algal beds, which is the case in the vicinity of Wilson Creek, Spring Creek and Mountain Creek Bridge, and which in the last vicinity accounts for the anomaly in the isopach map. (See below.)

I/S ratio map

This is a contour map of the ratio, total thickness intertidal rocks/total thickness subtidal rocks, and is obtained by dividing the combined thickness of the Flaggy and Yellow Limestone members, by the combined thickness of the remaining members. It is a measure of 'non-marineness'. Progressively higher values indicate direction of land, which according to the map (Fig.14) lies to the northwest and south-east. Again there is an anomaly in the vicinity of Mountain

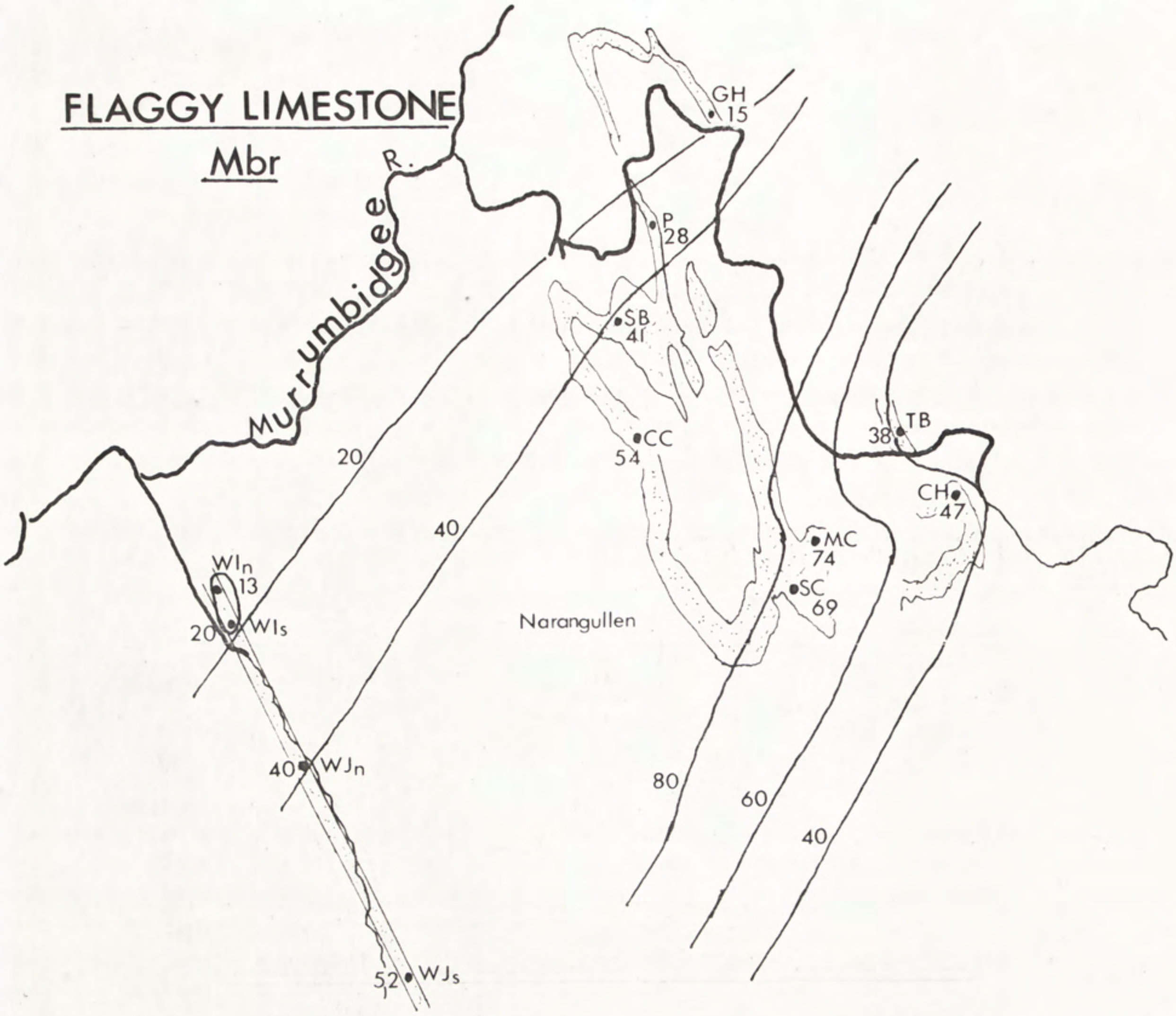
TEXT FIG.12. ISOPACH MAP, TOTAL THICKNESS OF THE CAVAN LIMESTONE

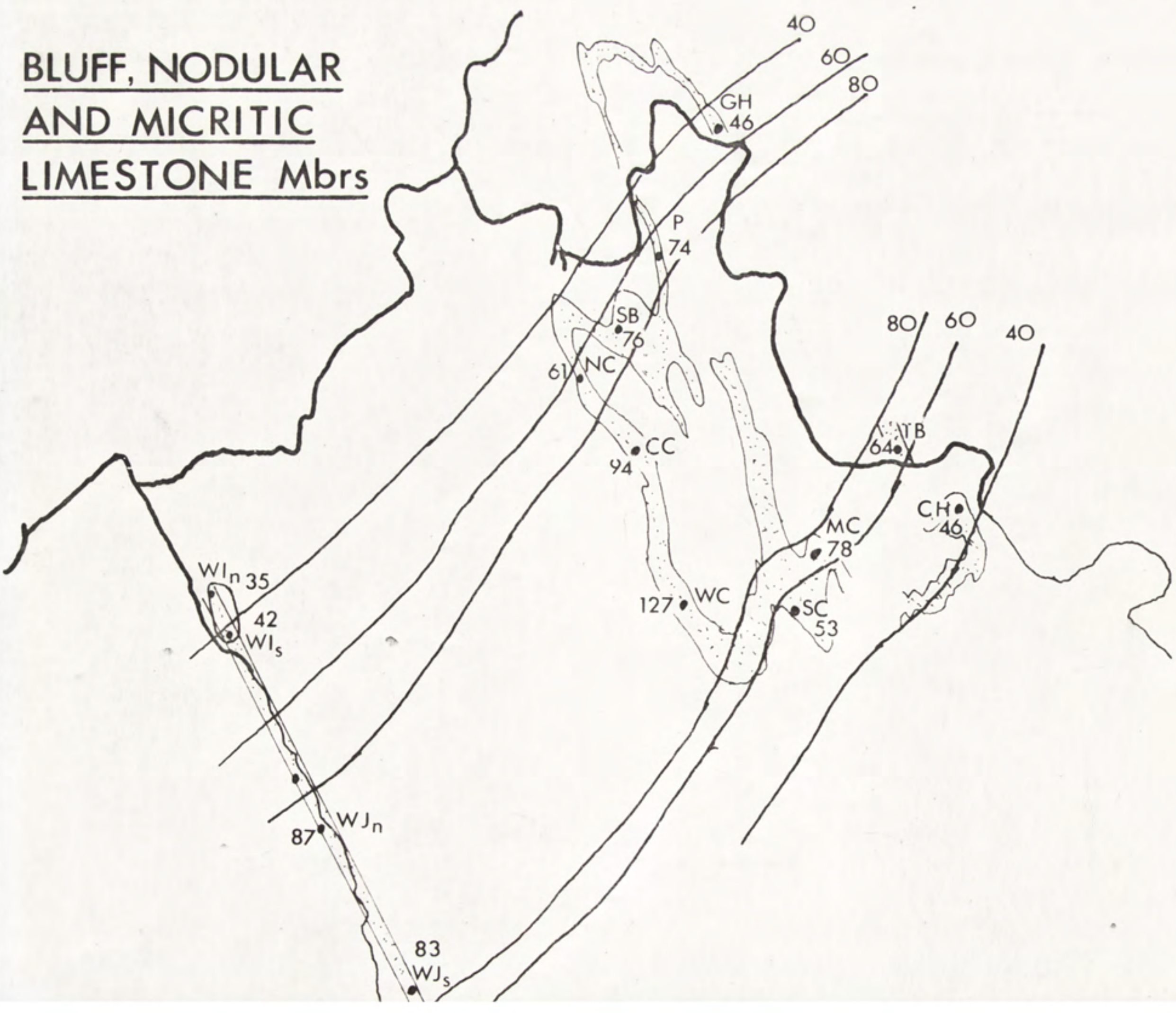


WI_n	Wade Island north	MC	Mountain Creek Bridge
WI_s	" " south	CH	Clear Hill
WJn	Wee Jasper north	TB	Taemas Bridge
WJs	" " south		
GH	Good Hope		
P	Peninsula		
SB	Salt Box		
NC	Narrangullen Cave		
CC	Chimney Creek		
WC	Wilson Creek		
SC	Spring Creek		
CV	Cave Valley		

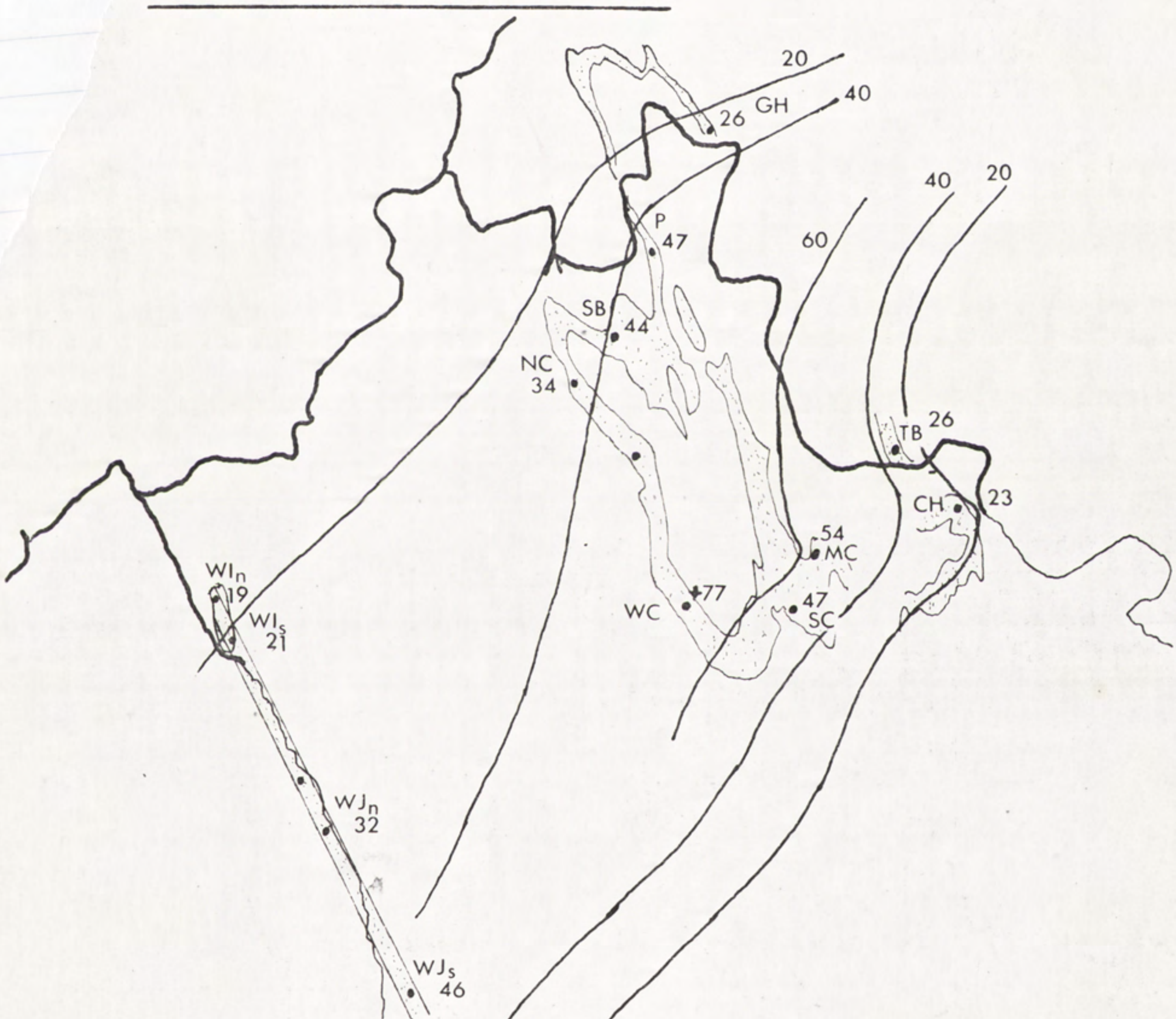
8 km

TEXT-FIG.13. ISOPACH MAPS OF THE CAVAN LIMESTONE

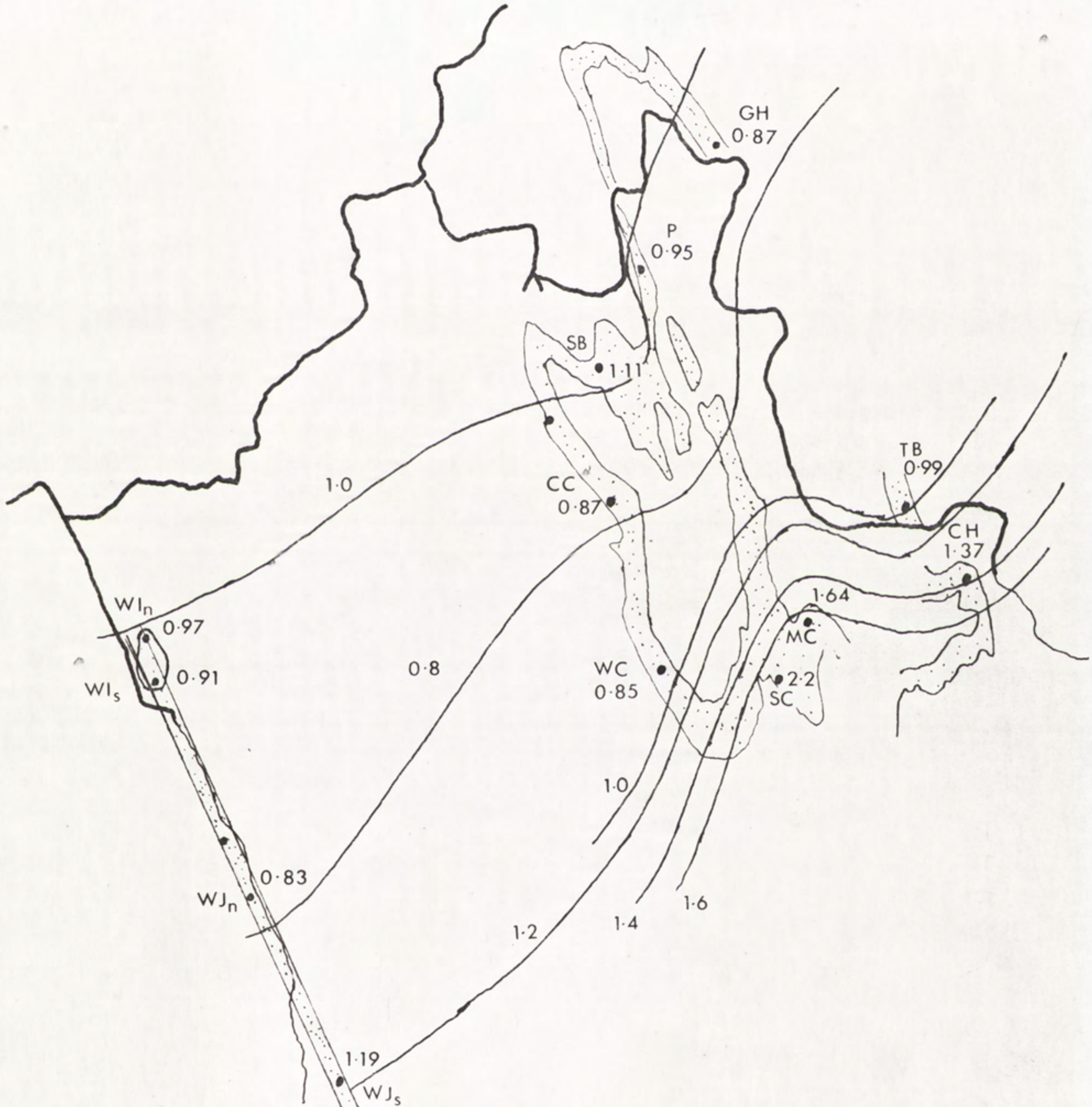

FLAGGY LIMESTONE
Mbr
Murrumbidgee R.
GH
15
P
28
SB
41
CC
54
TB
38
CH
47
MC
74
SC
69
Narangullen
WIn
13
20
WIs
40
WJn
52
WJs
20
40
80
60
40


BLUFF, NODULAR
AND MICRITIC
LIMESTONE Mbrs
40
60
80
GH
46
P
74
SB
76
61
NC
CC
94
80
60
40
TB
64
CH
46
MC
78
127
WC
SC
53
WIn
35
42
WIs
87
WJn
83
WJs

YELLOW LIMESTONE Mbr



TEXT-FIG. 14. I/S MAP



Creek Bridge, which is explained by the great thickness of algal strata which are non-marine, and thus give a high value.

Lithology

Calcretes which signify considerable periods of emergence are more common towards the northwest (for example, at Wade Island and at Good Hope) and to the southeast (for example, at Clear Hill). This trend is also apparent in the frequency of occurrence of birdseye and other desiccation structures, which indicate exposure to the atmosphere. However, the Flaggy and Yellow Limestone members to which calcretes are confined, and which show the most prominent desiccation features, are often very recessive and not exposed. In fact, this general lack of good exposure negated any attempts at constructing meaningful lithofacies or lithological ratio maps (except the I/S map).

The presence of landmasses implies boundaries to the basin, but the actual location of these cannot be specified, because it is not known how far the Cavan Limestone extended northwest of the northern arm of the Murrumbidgee River, and because to the southeast, there is extensive faulting. Nevertheless, the width of this basin was at least 15 km (which is the distance between Wee Jasper south and Cave Island), and most likely, from regional considerations, was about 20 km. Obviously, the shorelines fluctuated greatly, and, from the previous discussions, trended northeast. It is apparent that the trend of later tectonics, giving the present structural configuration, has been right across the trend of the Cavan Limestone basin. This relation is characteristic of some Palaeozoic sequences in the Rocky Mountains, where later structures have cut across earlier sedimentary and tectonic trends (Krumbein & Sloss, 1963).

The question naturally arises as to the possibility of a closure of the basin, whether to the northeast or southeast. At present there is no way of determining this. The main reason is because of a lack of control points, especially towards the centre of the area, and unfortunately during non-drought times, along the banks of the Murrumbidgee and Goodradigbee Rivers. This is particularly unfortunate in the area to the southwest of Good Hope, where thickness measurements are rather critical. In addition, to the south of Good Hope, apparently the Cavan Limestone has been faulted out to a large extent. This naturally limits interpretations regarding a closure, which possibly may have existed towards the northwest, since the Good Hope and Taemas Bridge sections, as shown by the d.e. curves, are very similar, and because of the presence of some calcretes to the southwest of Good Hope. If this were the case, however, severe restrictions to circulation could have been expected with the possible formation of evaporites. These are not present in the Cavan Limestone, but this could be explained by a relatively humid climate. In this connection, it is interesting that to the northwest, in the Canning Basin of Western Australia, evaporites (of the Carribuddy Formation) were possibly forming during Cavan Limestone times (Johnson *et al*., 1967), suggesting that there, conditions may actually have been more arid.

6.3 GEOLOGICAL HISTORY OF THE CAVAN LIMESTONE

During the Early Devonian, great thicknesses of rhyolitic lava, tuff and ash (Black Range Group) were deposited in the area as a result of widespread volcanic activity. With the gradual cessation of this activity and the corresponding decrease in the rate of deposition, allied with slow but steady subsidence, there may have been a depositional transgression (Curray, p.191, 1964), during which the Fifeshire Formation was deposited in very shallow water.

Flaggy Limestone Member

With increasing stability, conditions became more favourable for carbonate deposition and an extensive carbonate tidal flat complex was formed. This was greatly affected by the presence of a terrigenous delta, which, especially during early Flaggy Limestone Member times, may have prograded across the flats. No doubt this was during times of pronounced terrigenous influx, concomitant with a few remaining bursts of volcanic activity on the highlands, to the northwest and southeast.

This tidal flat probably occupied the whole basin, although there may have been permanent bodies of water towards the centre. In contrast, towards the margins slightly more elevated areas were emergent for considerable periods of time, which was conducive for the formation of calcretes. Elsewhere, especially in the vicinity of Mountain Creek Bridge and Spring Creek, algal mats flourished, probably due to optimum salinity conditions, and, as a result, large thicknesses of algal rock accumulated (producing the thickness anomaly apparent from the isopach maps).

The depositional interface of these flats had little relief or slope, and broad areas were regularly inundated and exposed by periodic changes in water level, whether as a result of lunar tides or seasonal climatic changes.[1] Probably rate of sediment supply and exposure to wave action (by analogy with

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[1] The intertidal areas of the northwestern part of France in the Mont. St Michel area might serve as a modern analogue, although it is primarily a non-carbonate sedimentary environment. Here the tidal flats are exposed twice a day across an area 19 km wide (Philiponneau, 1956).

the Bahamas [Shinn, Lloyd & Ginsburg, 1969]), imposed upon a background of increasing tectonic stability and steady subsidence, were the controlling factors in determining regressive or transgressive sequences. However, these are not well shown by the d.e. curves, probably because the grading of the intertidal environments is not fine enough. This is especially the case for the Taemas Bridge and Mountain Creek Bridge curves, which would show appreciable variation if some of the terrigenous beds were actually subtidal. It is conceivable, however, that some of the calcretes (G.H. 1, 2, 6, 7, 8, 9) may in part signify regressive sequences. Minor depositional transgressions are represented by G.H. 4; T.B. 3, 4; C.H. 5; and H.S. 3, 5. Interestingly, during feature 4 times, lagoonal conditions obtained in the vicinity of Good Hope, while to the southeast, conditions were more open, and highly fossiliferous sediments were forming.

Bluff Limestone Member

Under conditions of steady subsidence and moderate rate of deposition, the tidal flats, in most areas at any rate, became completely submerged by shallow water. In the vicinity of Clear Hill there was a steady progression from intertidal to lagoonal to open subtidal conditions (C.H. 10, 11, 12), while to the northwest, around Good Hope, there was a series of minor transgressions and regressions (for example, T.B. 11). In the Taemas Bridge area there was almost continuous deposition of skel-algal sediments. All this suggests differences in sedimentation related to local differential subsidence and hydrological conditions.

During upper Bluff Limestone Member times, there may have been a temporary rejuvenation of the land mass or a change in climate, with a corresponding increase in the rate of terrigenous sediment supply, which reversed the general pattern of sedimentation and caused a minor depositional regression. This is most marked in the Good Hope area (G.H. 13) where thick-bedded sandstones accumulated (if indeed these are intertidal). Elsewhere lagoonal conditions (C.H. 13), and areas of terrigenous and pelletal mud accumulation (T.B. 13 and M.C. 13) existed.

Nodular Limestone Member

This last event was temporary and possibly with the cessation of volcanic activity, the whole area was submerged under a continuous cover of water. The delta migrated landwards. For a while there were still some spasmodic terrigenous influxes (G.H. 14), but these soon died out. About this time, also, pelletal rocks were forming around Taemas Bridge (T.B. 14).

However, generally conditions were now favourable for the proliferation of an abundant and varied biota, and at many places within these warm, shallow and moderately well-aerated waters, Cystiphyllum biostromes and echinoderm banks and meadows flourished. This was the time of maximum extent of this sea which was about 20 km wide. The picture was one of stability, with sedimentation keeping pace with steady subsidence. However, there were periodic incursions by fine detrital material, so that at regular intervals considerable amounts of clay and marl were deposited.[1] This rhythmic bedding may be ascribed either to periodicity in the factors

[1]This rhythmic sedimentation was subsequently followed by the rhythmic unmixing of the calcium carbonate with respect to the clay (Sujkowski, 1958). This would differentiate the more marly sediments into alternating thin bands of lime-rich and lime-poor marl. Apparently, such a theory combined with extreme differences in compaction, could explain the origin of the distinctive nodularity of many of the skeletal rocks.

determining precipitation of the calcium carbonate, or to periodicity in the transportation and deposition of argillaceous matter (Hadding, 1958). Most probably, however, a combination of these two possibilities was operative and caused by regular climatic changes. What these were is highly speculative, but they could comprise, for instance, a regularly returning rainy period with washing-out of mud and simultaneous freshening of the wea-water, alternating with a dry, warm period with little supply of mud, increased temperature, increased evaporation, and more abundant deposition of calcium carbonate.

Micritic Limestone Member

These conditions were brought to a close by both a marked change in the hydrodynamic energy and fauna within the basin, even though for a while, periodic influxes of fine detritus persisted (T.B. 18 and G.H. 18). The diversity and abundance of the fauna were greatly reduced, but echinoderm banks may still have flourished as in the vicinity of Mountain Creek Bridge. However, over much of the area unfossiliferous carbonate muds were accumulating. The change was generally rapid, except in the Clear Hill area where skeletal material accumulated for a while (C.H. 19 and 20), and implies the rapid formation of some sort of barrier which severely restricted circulation, and resulted in a widespread area of lagoonal sedimentation.

Yellow Limestone Member

Probably during the deposition of the Nodular Limestone Member there was a slight slowdown in the rate of subsidence caused by epeirogenic or eustatic events. As this continued it gave rise to a major regression, during which the whole of the area was again formed into a tidal flat complex. Extensive areas of this were exposed to the atmosphere for considerable times as indicated by the abundance of calcretes. Marine incursions were very rare, but occasionally there may have been a partial return of the sea, giving rise for example, to lagoonal conditions at several places (T.B. 21, 24 and C.H. 24, 29). Just as the Nodular Limestone member represented the time of maximum submergence, this member marked the time of maximum emergence.

Together with the calcretes, microspar wackestones, gastropod wackestones and algal limestones (the last, almost to the exclusion of other rock types in the vicinity of Mountain Creek Bridge) were in the process of formation, probably in some form of cyclical arrangement. However, the only obvious cycles are represented by the calcrete-gastropod wackestone alternations, which are apparent from the tree diagram of Good Hope (Fig.5a), and best shown on the d.e. curve between features G.H. 30 and G.H. 36, and probably present, but poorly exposed, at C.H. 29 - C.H. 38. Quite likely they reflect a climatic control, with the calcretes forming during less humid or warmer periods. Other patterns include the sequences algal limestone → gastropod wackestone → calcrete, and gastropod wackestone → calcrete → microspar wackestone. The first is a regressive sequence, apparent from the Markov analysis (Fig.5a), but not so obvious from the log (G.H. 26, 27, 28). The second (G.H. 35 - base of G.H. 39) is not indicated at all from the Markov analysis, because of its rarity. Probably, as in the deposition of the Flaggy Limestone member, rate of sediment supply and exposure to waves were the controlling factors determining such sequences. However, as pointed out by Shinn _et al_. (1969, p.1225), meandering tidal channels can produce regressive (and transgressive) sequences. Such large tidal channel structures of the type associated with the meandering channel systems described by Shinn et al. for Andros Island, were not observed in the Cavan Limestone, and such an origin is therefore not favoured.

Throughout these times, terrigenous sedimentation, predominantly of fine detritus, continued, and occasionally was quite appreciable, possibly reflecting times of greater stream discharge.

Upper Fossiliferous Limestone Member

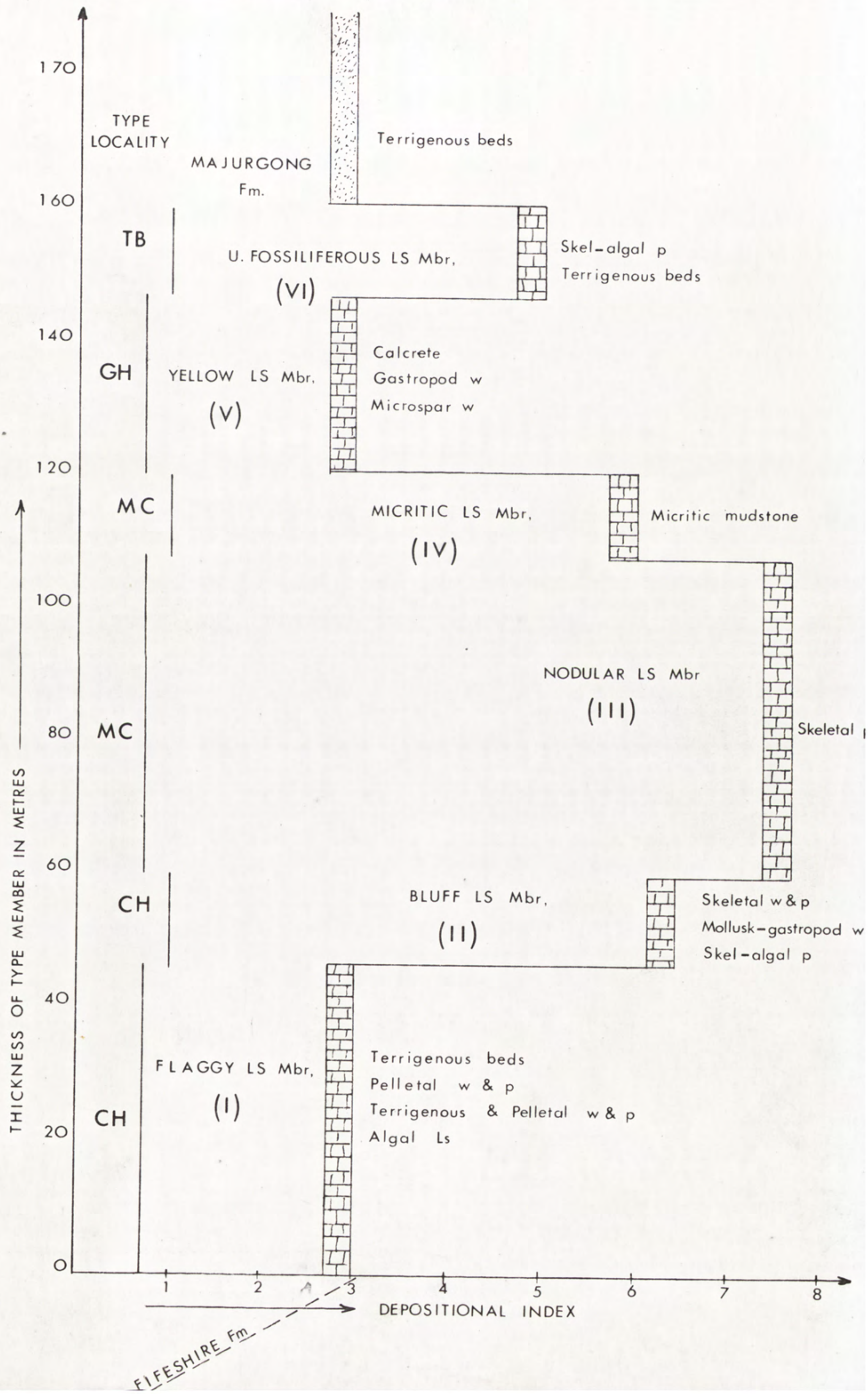
In most places this was marked by a return of the sea. In the Taemas Bridge area there was an appreciable increase in the rate of subsidence,which resulted in a rapid erosional transgression (Curray, p.200, 1964). As a consequence, in that area a series of calcretes is directly overlain by a thick sequence of skel-algal rocks, the latter attesting to almost continuous deposition of skel-algal sediments for the remainder of Cavan Limestone times. Elsewhere, as around Clear Hill, subsidence was not so rapid, and there was a progression from lagoonal (C.H. 44) to open subtidal sedimentation. However, apparently in the Good Hope area, the sea did not return at all and possibly there was extensive soil formation (parts of G.H. 43,may actually be equivalent to this member).

Towards the end of Cavan Limestone times, terrigenous sediments became more dominant (T.B. 46), possibly heralding, with the decreasing rate of subsidence, the advance of an extensive terrigenous delta, which eventually prograded over the whole area and deposited the Majurgong Formation.

6.4 CONCLUDING REMARKS

Fig.15 is a graph of the thickness of the six

TEXT-FIG. 15. GRAPH OF THICKNESS OF TYPE MEMBERS AGAINST AVERAGE DEPOSITIONAL INDEX



individual type members combined into a composite type section of the Cavan Limestone, plotted against the average depositional index of each member. From this, the megacyclicity of the Cavan Limestone is apparent. It comprises a transgression (Members I, II and III) followed by a regression (Members IV and V), and then another transgression (Member VI), followed by a regression (Majurgong Formation). Each of these phases is actually the summation of both mezzo-cycles[1] and minor transgressions and regressions.

The actual controls of this megacyclicity are open to debate. A tectonic control was present at the commencement of the cycle, in the sense that, with the cessation of volcanicity and the corresponding decrease in supply of terrigenous sediment, carbonate sedimentation may have been initiated by default. Thereafter, there was possibly primarily a climatic control which radically affected the rate of deposition, an increased rate resulting in regression, a decreased rate in transgression. The former process could, for example, account for the incoming of the Majurgong Formation, as volcanicity does not seem to have been dominant at that time. No doubt, superimposed on all this were local sea floor topographic changes (epeirogenesis), as evidenced during the deposition of the Upper Fossiliferous Limestone Member. The small cycles probably were the result of processes intrinsic to sediment transport and deposition.

In conclusion then, it is tentatively advanced that the differences in sedimentation during the Cavan Limestone were related to local differential subsidence and hydrography.

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[1]Cycles on a metre scale.

This was superimposed on an overall cyclic pattern of subsidence and emergence, caused ultimately by climatic and epeirogenic events. It should be realised that "it is manifestly ludicrous to attempt to find a single control for cyclic sedimentation"(Duff, Hallam & Walton, 1967, p.242).

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      PROGRAM MARKTEST
C
      INTEGER DEGF
      DIMENSION E(20,20)
      DIMENSION T(20,20),P(20,20),LAMBDA(20,20)
      DIMENSION S(20),HTOT(20),VTOT(20)
      DIMENSION TITL(10),FMT1(7),FMT2(7),LET(20),MING(3)
C
      REAL LAMBDA
      DATA (IBL=1H),(MARG=2RMG)
      DATA (MING=24H(XR2,XOOF6,0,F12.0)     )
      DATA (LET=2R A,2R B,2R C,2R D,2R E,2R F,2R G,2R
                H,2R I,2R J,2R K,2R L,2R M,2R N,2R O,2R
                P,2R Q,2R R,2R S,2R T)
C
C
C        READ TITLES, CONTROL CARD
    2 READ 100,TITL
  100 FORMAT (10A8)
      IF (EOF,60) 50,3
   50 STOP
    3 PRING 100, TITL
      READ 101, N,KRIS, FMT1,FMT2
  101 FORMAT (6XI3,I1,7A5,7A5)
      MING(1)=MING(1) ,AND, 77777777777777700B
      NTEN=(N/10)*64 $ NUNIT=MOD(N,10)
      MING(1)=MING(1),OR,NTEN,OR,NUNIT
C
C        READ TALLY MATRIX, COMPUTE ROW-COLUMN SUMS
      DO 4 I=1,N
    4 READ FMT1,(T(I,J),J=1,N)
      TOT=0.0
      DO 5 I=1,N
    5 HTOT(I)=VTOT(I)=0.0
      DO 7 I=1,N
      DO 6 J=1,N
      HTOT(I) = HTOT(I) + T(I,J)
    6 VTOT(J) = VTOT(J) + T(I,J)
    7 TOT = TOT + HTOT(I)
C
C        READ OR COMPUTE PROBABILITY MATRIX
      GO TO (8.10) KRIS
    8 DO 9 I=1,N
    9 READ FMT2,(P(I,J),J=1,N)
      MESSG=8H (INPUT)
      GO TO 12
   10 DO 11 I=1,N
      DO 11 J=1,N
   11 P(I,J) = T(I,J) / HTOT(I)
      MESSG = 8HCOMPUTED
   12 PRINT 121,MESSG
      DO 16 I=1,N
   16 PRINT 107,LET(I),(P(I,J),J=1,N)
      PRINT 100, TITL
      PRINT 109
      CALL TRIALS(E,HTOT,N,20)
      DO 26 I=1,N
```

```
26 PRINT 104,LET(I),(E(I,J),J=1,N)
   DO 27 I=1,N
   DO 27 J=1,N
27 P(I,J) = P(I,J) - E(I,J)
   PRINT 209
   DO 28 I=1,N
28 PRINT 104,LET(I),(P(I,J),J=1,N)
   CHISQ = CHI(T,E,HTOT,N,20)
   PRINT 110,CHISQ
   DEGF = N*(N-2)
   PRINT 210,DEGF
   GO TO 2
C
104 FORMAT (3XR2,2X,16F8,3 / 7X,4F8,3)
107 FORMAT (XR2,X,20F6,2)
108 FORMAT (// 5X*P(J) ROW VECTOR*/ 5X,15(1H-)/ 4X,20F6,2)
109 FORMAT (//7X,*INDEPENDENT TRIALS MATRIX* / 7X,14(1H-)/)
110 FORMAT (//7X,*CHI SQUARE=*,F9,3)
121 FORMAT (// 5X*TRANSITION PROBABILITY MATRIX*, A15/
              5X,29(1H-)/)
130 FORMAT (//5*TALLY MATRIX INPUT* / 5X,18(1H-)
              //4X,22(4XR2))
132 FORMAT (X)
209 FORMAT (//7X,*DIFFERENCE MATRIX* / 7X,14(1H-)/)
210 FORMAT (//7X,*DEGREES OF FREEDOM=*,I10)
    END


    FUNCTION CHI (F,E,DIST,N,L)
    DIMENSION F(L,L),E(L,L),DIST(N)
    SUM=0.0
    DO 10 I=1,N
    DO 10 J=1,N
    A=DIST(I)*E(I,J)
    IF(A,EQ.0.0) GOTO 10
    R=(F(I,J)-A)**2
    SUM=SUM+R/A
 10 CONTINUE
    CHI = SUM
    RETURN
    END


    SUBROUTINE TRIALS(E,DIST,N,L)
    DIMENSION E(L,L),DIST(N)
    SUMD=0.0
    DO 10 I=1,N
 10 SUMD = SUMD + DIST(I)
    DO 20 I=1,N
    DO 20 J=1,N
    IF (I,EQ,J) 11,12
 11 E(I,J)=0.0
    GO TO 20
 12 E(I,J)=DIST(J)/(SUMD - DIST(I))
 20 CONTINUE
    RETURN
    END
```

PLATE I

1: Highly cleaved beds of the Yellow Limestone member near Mountain Creek Bridge. The dip is to the right.

2: Typical loose-nodular appearance of the Nodular Limestone Member. The dip is to the right.

PLATE II

1: Compact nodular habit in skeletal wackestones and packstones of the Nodular Limestone Member at Taemas Bridge. (Rule is 150cm long.)

2: Skeletal wackestone with echinoderm, brachiopod and mollusk fragments (X 12.5). Note typically fine-microspar plasma.

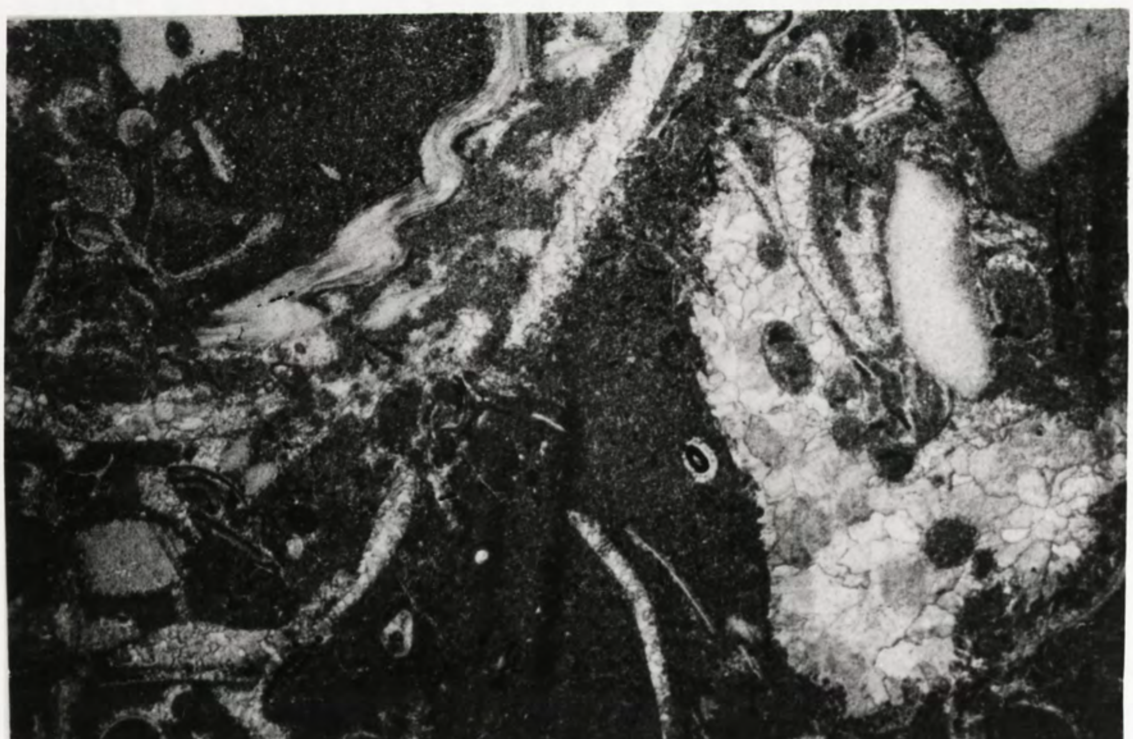


PLATE III

1: Neomorphic replacement of ?mollusk shell (X 125). Part of its original structure is delineated by pyrite.

2: LLH-S type of stromatolite. (Negative print of acetate peel, X 3.)

PLATE IV

1: Planar (smooth-mat) laminations in algal limestone. (Negative print of acetate peel, X 3.)

2: Tufted-mat laminations in algal limestone.


KONICA

PLATE V

1: Laminae in algal limestone emphasized by colour banding. The algal-rich laminae are darker in colour. (Negative print of acetate peel, X 3.)

2: Layer of skeletal debris, graded from fine at the base (to the left) to coarse at the top. (Negative print of acetate peel, X 3.)

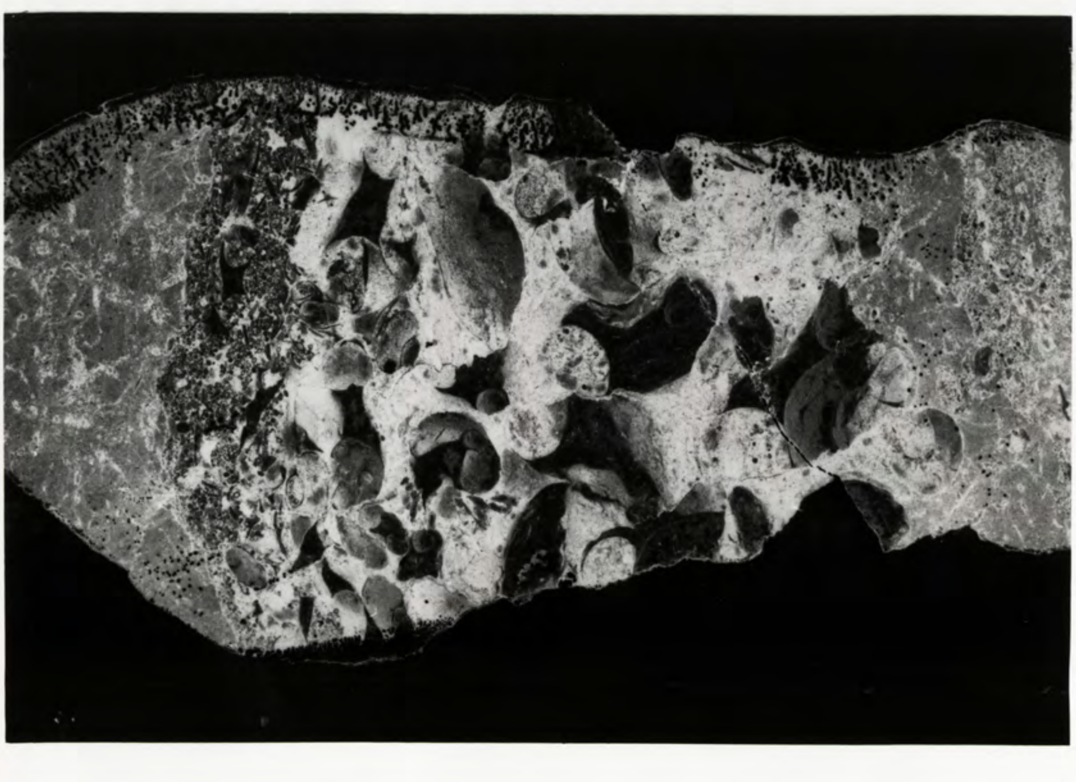


PLATE VI

1: Mudcracks in Flaggy Limestone Member at Mountain Creek Bridge. (Rule is 45cm long.)

2: Teepee structure in algal limestone from Flaggy Limestone Member at Mountain Creek Bridge. (Negative print of acetate peel, X 3.)

PLATE VII

1: Birdseye structure in algal limestone from Yellow Limestone Member at Clear Hill. (Negative print of acetate peel, X 10.)

2: Disrupted laminae in algal limestone from Flaggy Limestone Member at Mountain Creek Bridge. The lowermost lamina is only slightly disturbed. Above there has been intense fragmentation. (Negative print of acetate peel, X 3.)

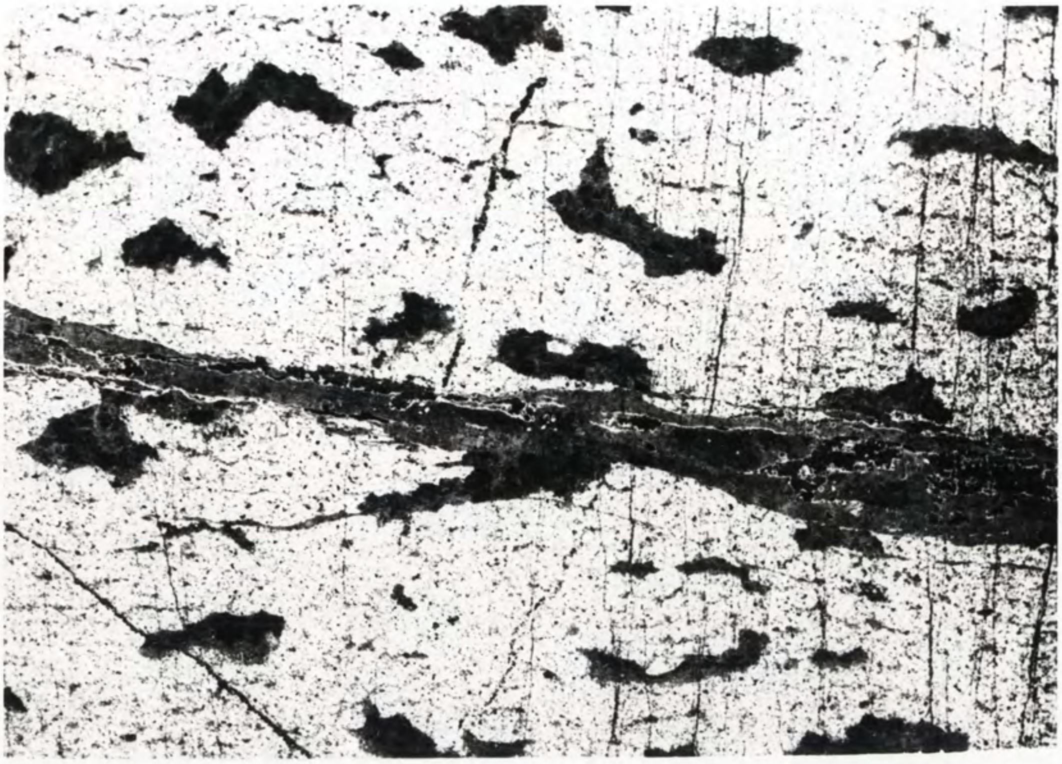


PLATE VIII

1: Vertical burrows (t) disrupting algal laminae in algal limestone, from Flaggy Limestone Member near Mountain Creek Bridge. (Negative print of acetate peel, X 3.)

2: Crenulate light and dark algal laminae in thin section (X 12.5).

PLATE IX

1: Cryptocrystalline calcite (t) formed from the recrystallization of algal tubules, enclosing laminae showing faint traces of vertically-oriented algal threads (X 50).

2: Massive calcrete bands in the Yellow Limestone Member at Clear Hill.

PLATE X

1: Laminae (t) in calcrete vaguely defined by differential staining (X 50).

2: Calcite (t) replacing quartz grain in calcrete. (Crossed nickols, X 125).

PLATE XI

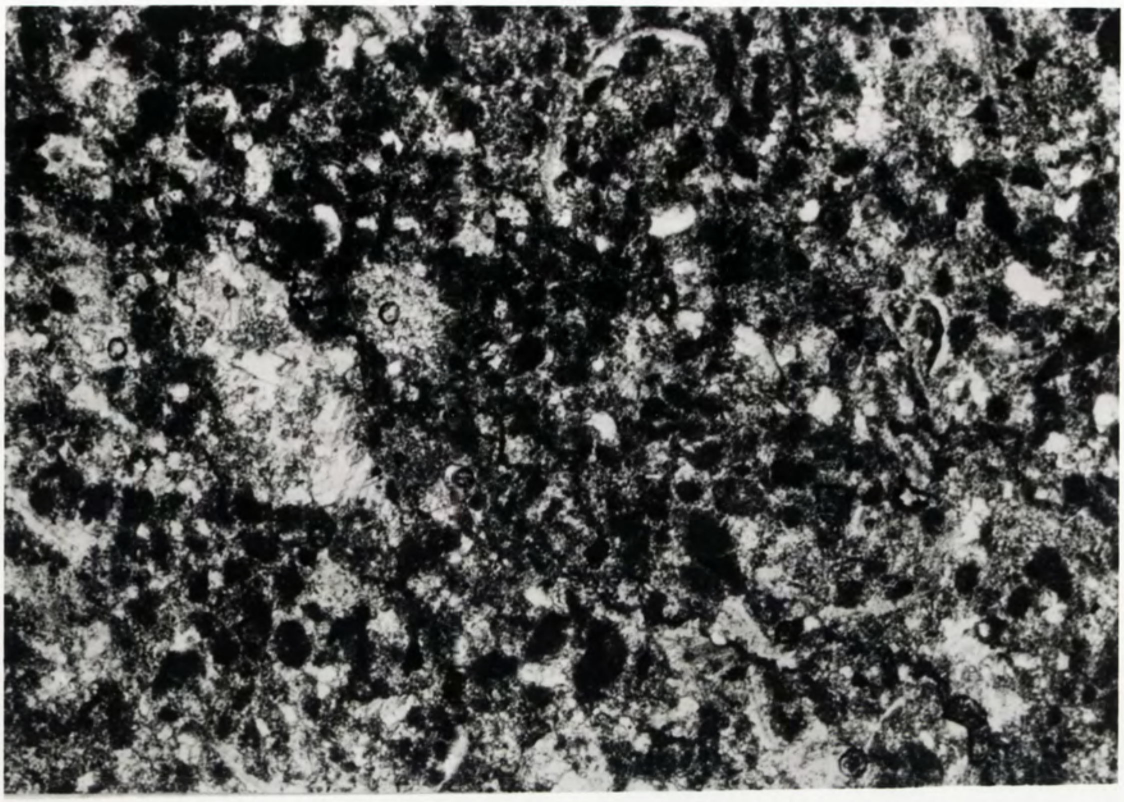
1: LLH S-mat type laminations in calcrete.
(Negative print of acetate peel, X 3.)

2: Birdseye structure in calcrete.
(Negative print of acetate peel, X 4.)

PLATE XII

1: Faecal pelletal packstone (X 50). Note fine-microspar plasma, and small size of pellets.

2: Typical outcrop appearance of skel-algal packstones. Note regular bedding. (Rule is 180cm long.)



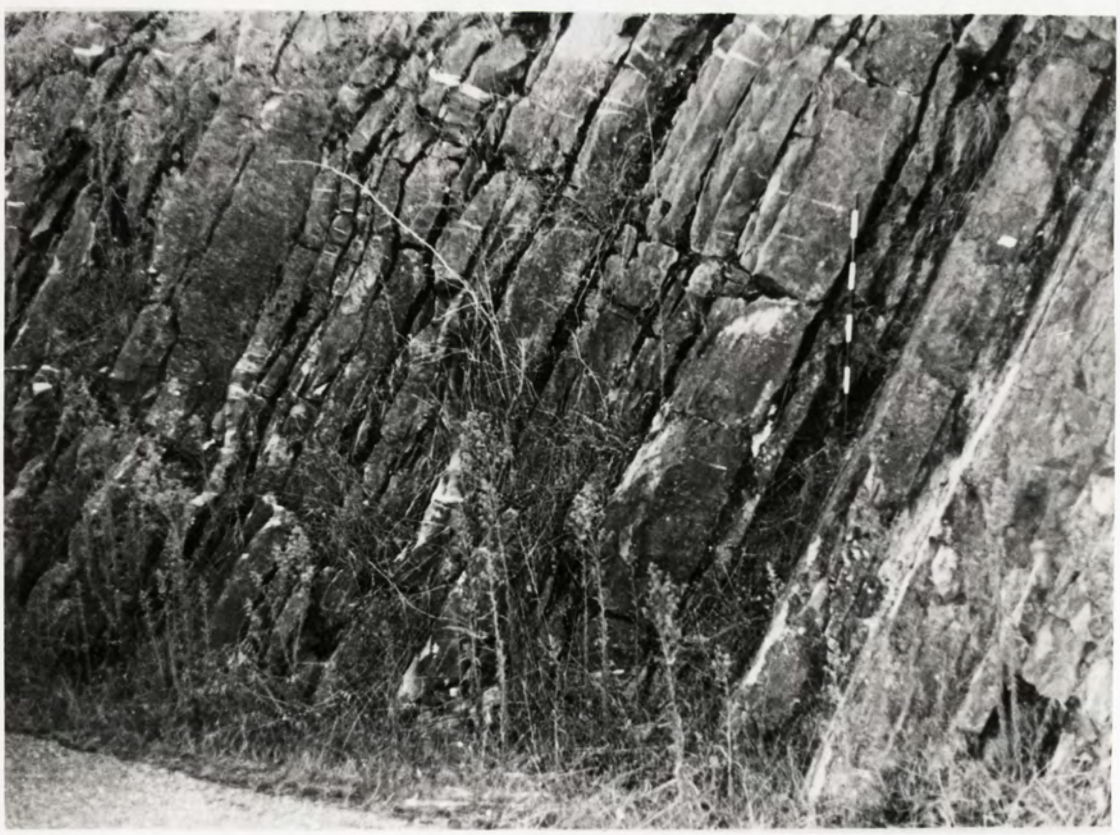
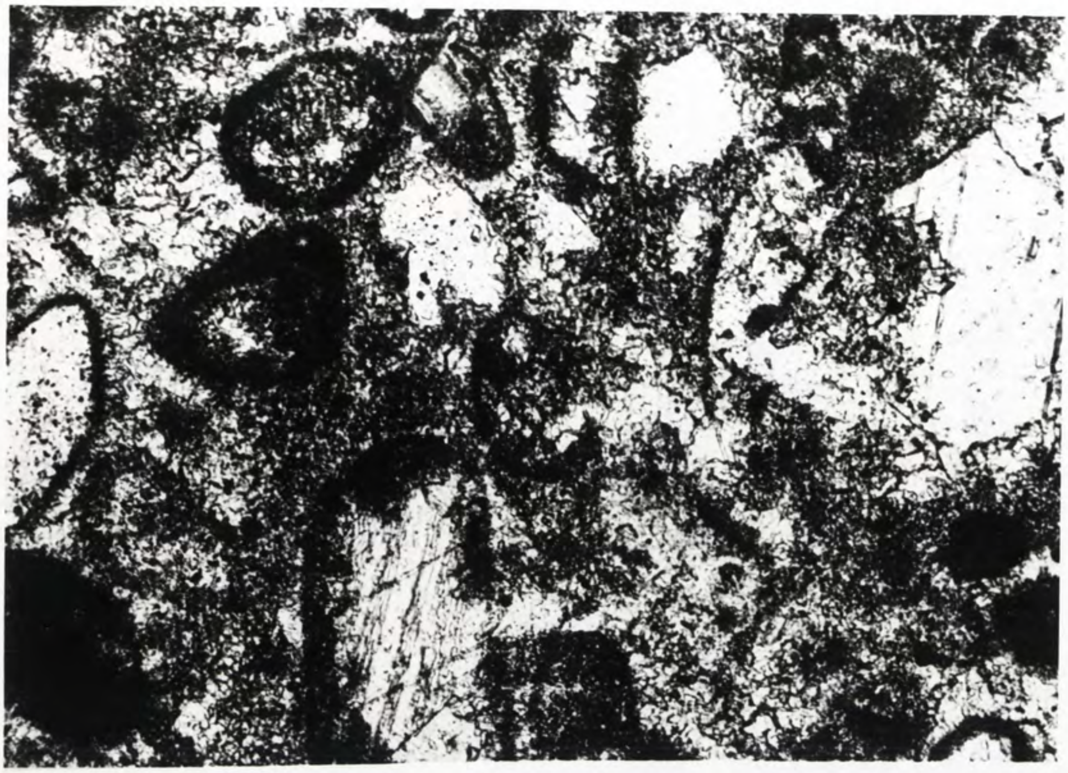


PLATE XIII

1: Partial destruction of skeletal debris by algae (X 50).

2: Skel-algal pellets. Note their relatively large size, and also the incipient corrosion of the echinoderm fragment (t), which displays a syntaxial rim (X 50).



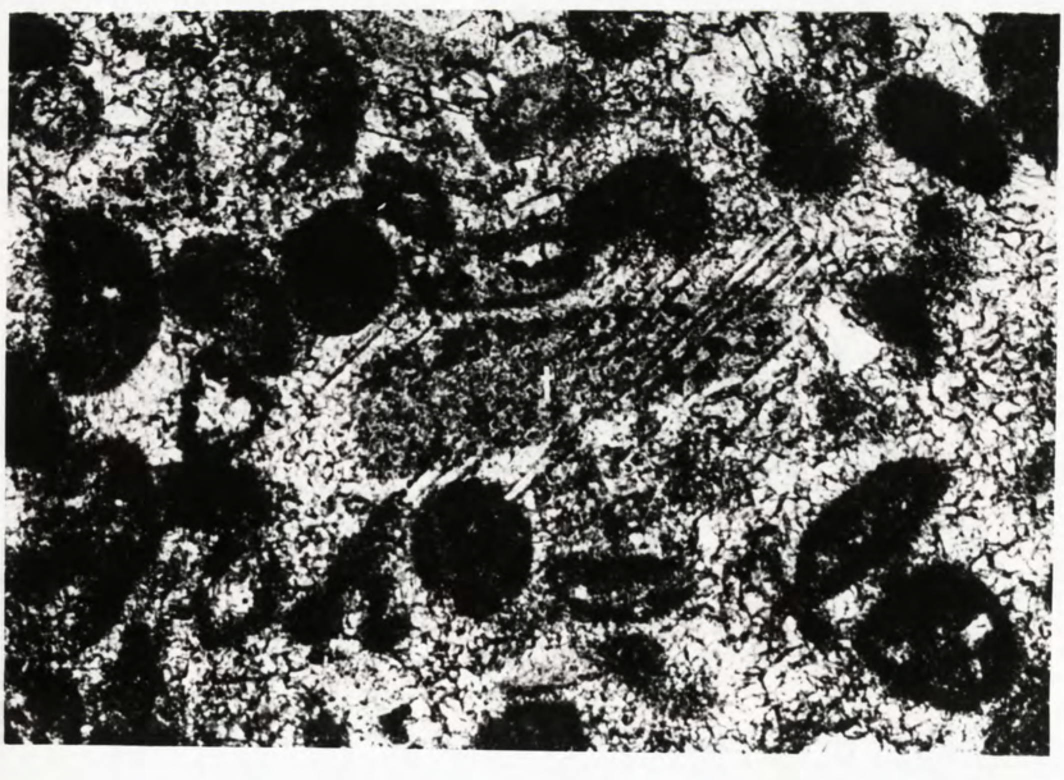


PLATE XIV

1: Sooty pyrite replacing skeletal fragment (t) in skel-algal packstone (X 50).

2: Complete replacement of mollusk shell by feldspar, except for micritic rims (X 50).

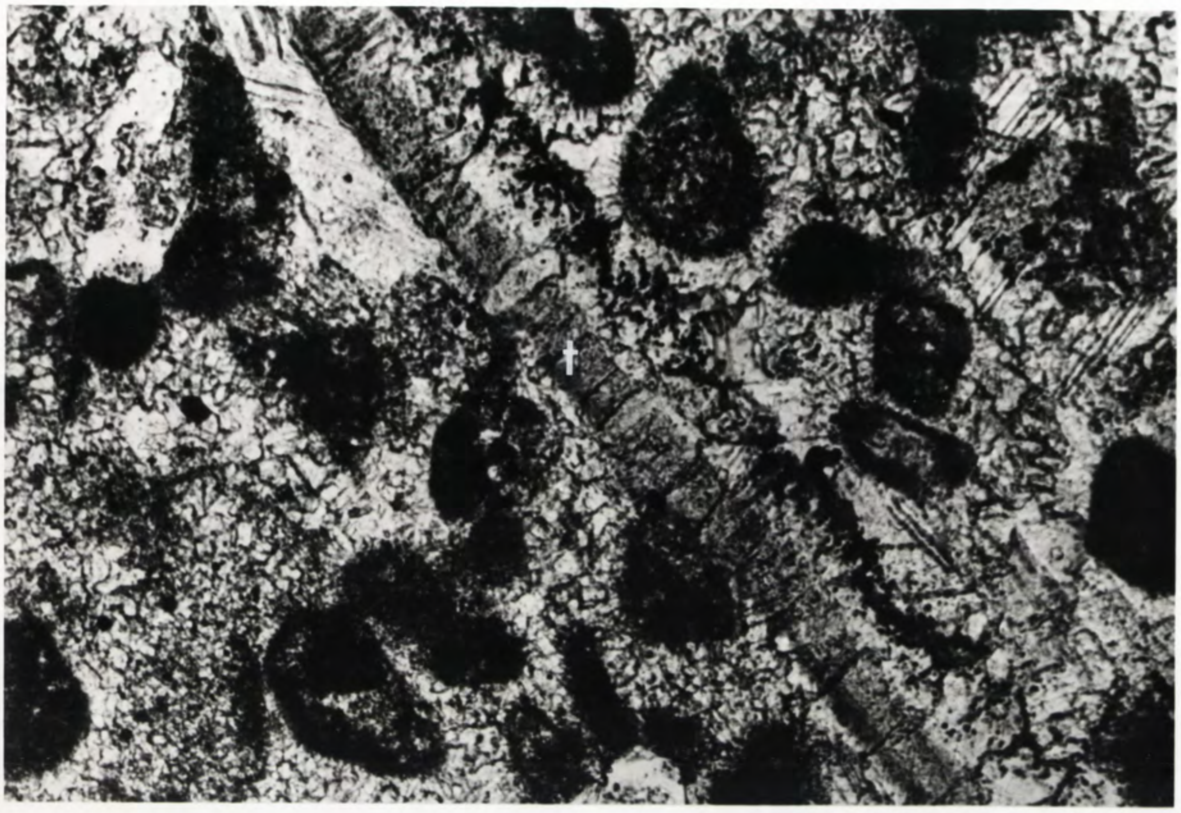


PLATE XV

1: Complete replacement of mollusk shell by feldspar, except for micritic rims (crossed nickols, X 50).

2: Feldspar grain growing across skel-algal fragment (X 125).

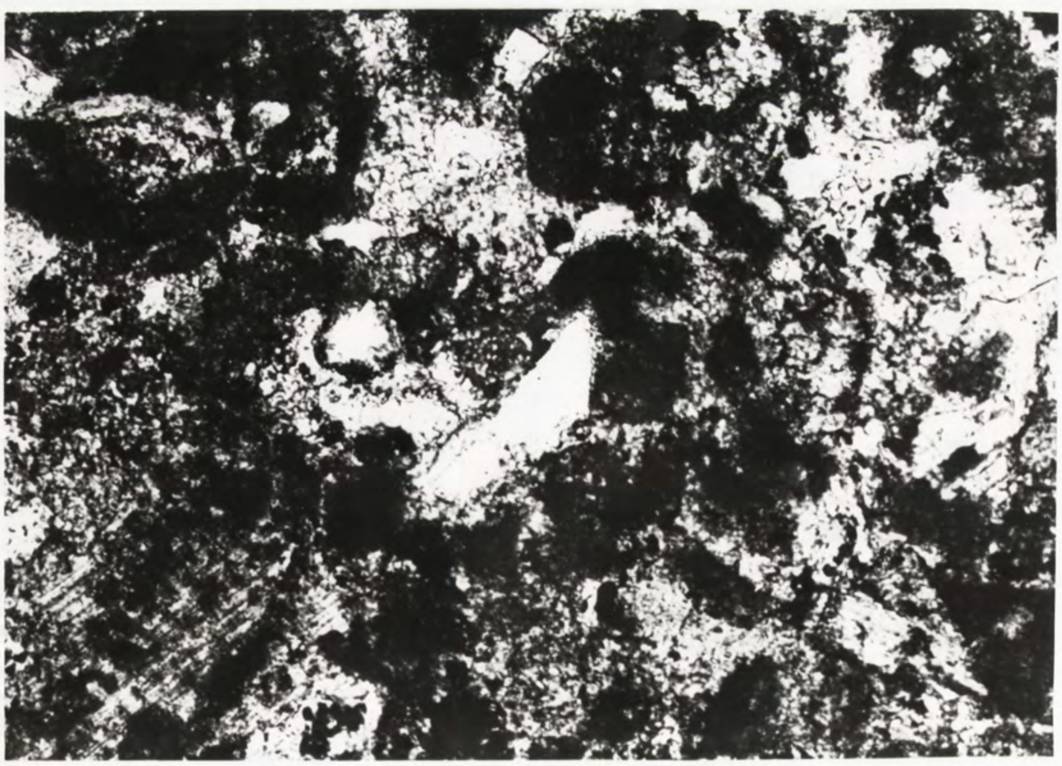
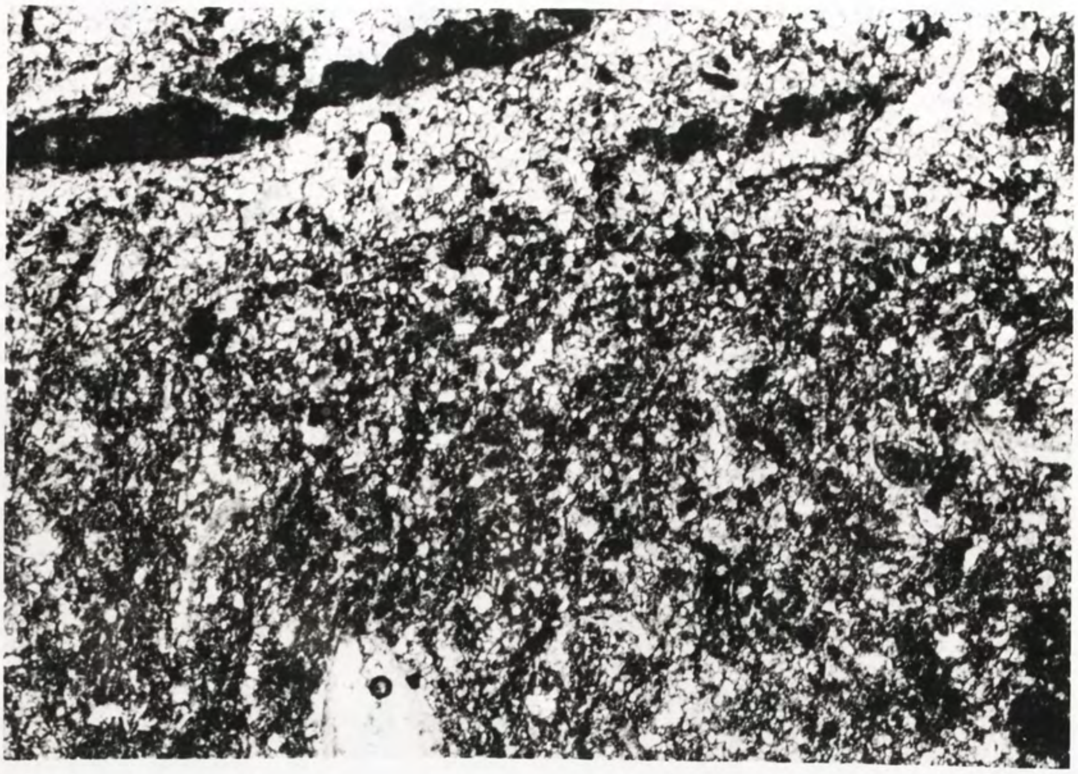


PLATE XVI

1: Typical paucity of allochems in microspar wackestone (X 50).

2: Terrigenous and pelletal packstone (X 50). Note fine-microspar plasma and small size of pellets.



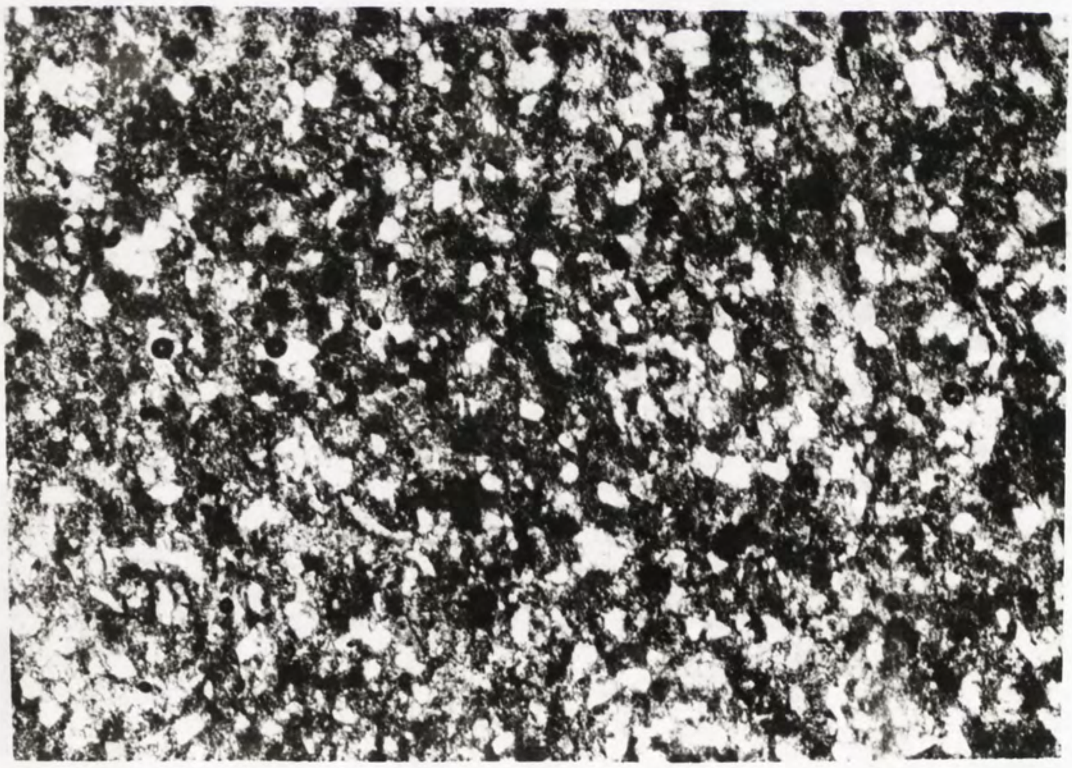


PLATE XVII

1: Micritic mudstone (X 20).

2: _Sphaerocodium_ sp., occurring in micritic mudstone (X 50).

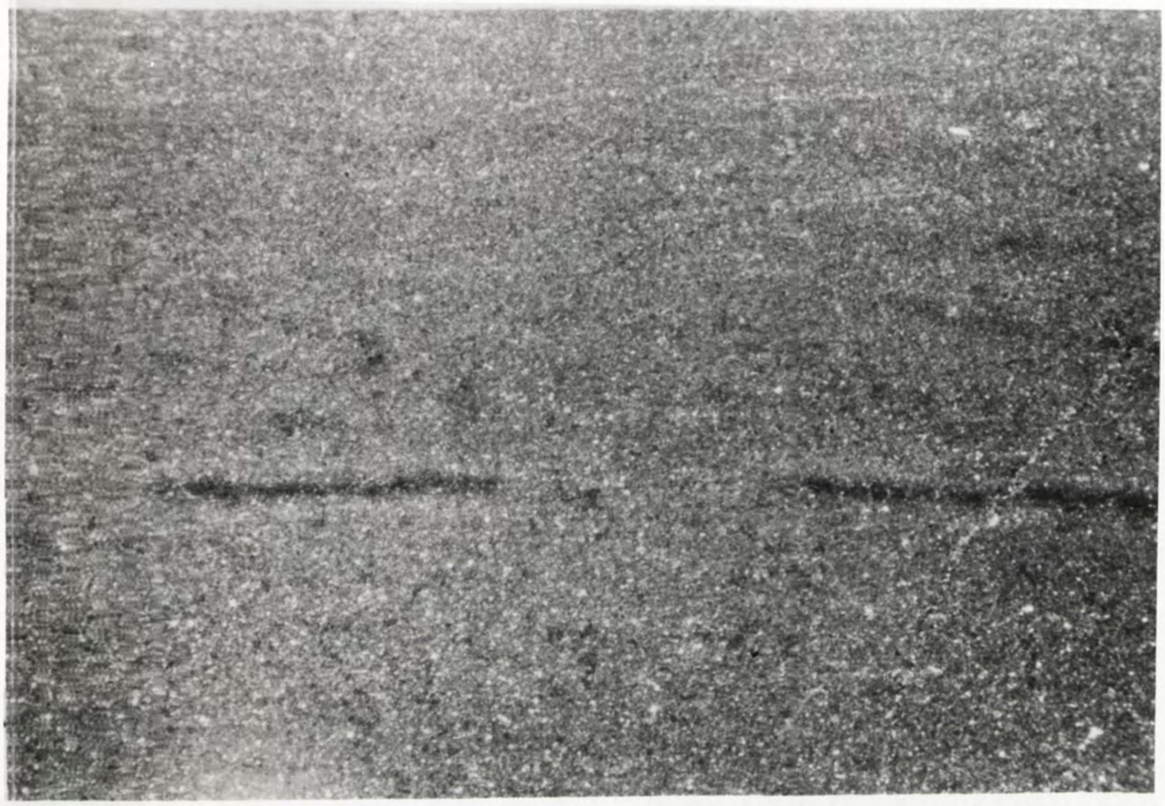


PLATE XIX

1: Gastropod wackestone showing complex relationship between drusy mosaic and fine grey microspar of extensively reworked gastropod fragments (X 12.5).

2: Mollusk-gastropod wackestone showing fragmental nature of the skeletal debris (X 50).

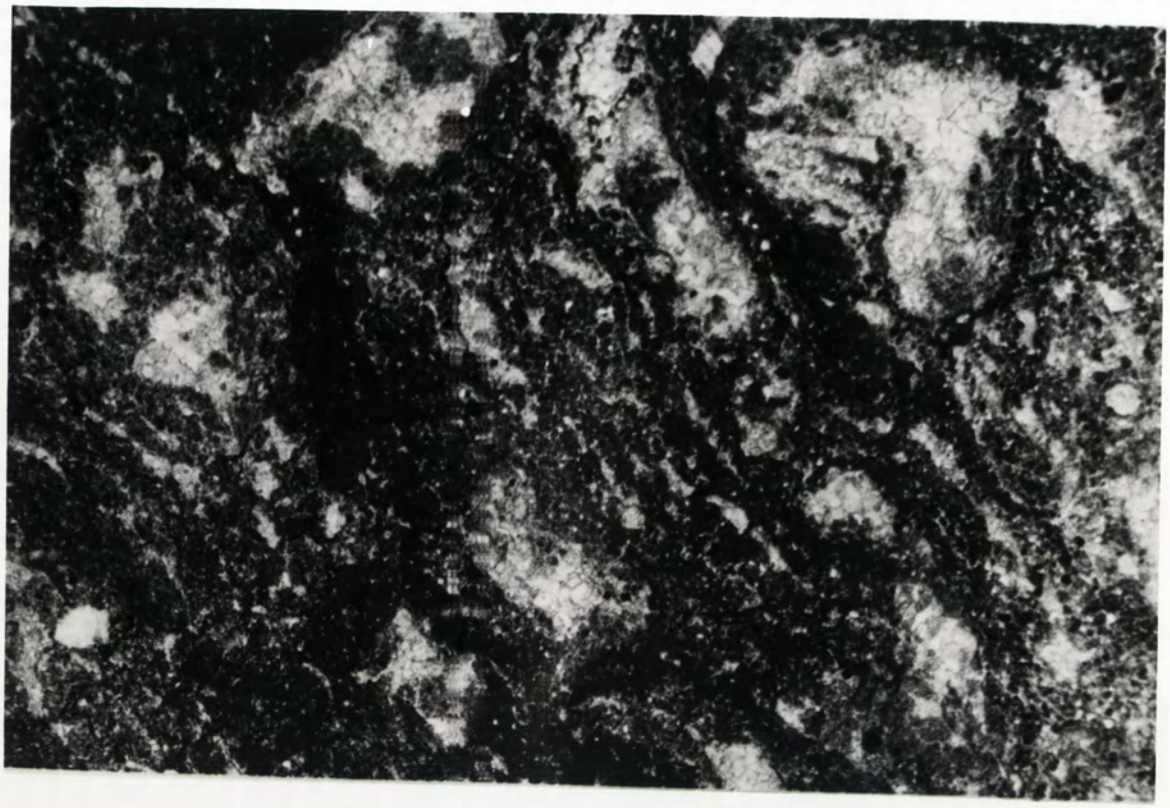
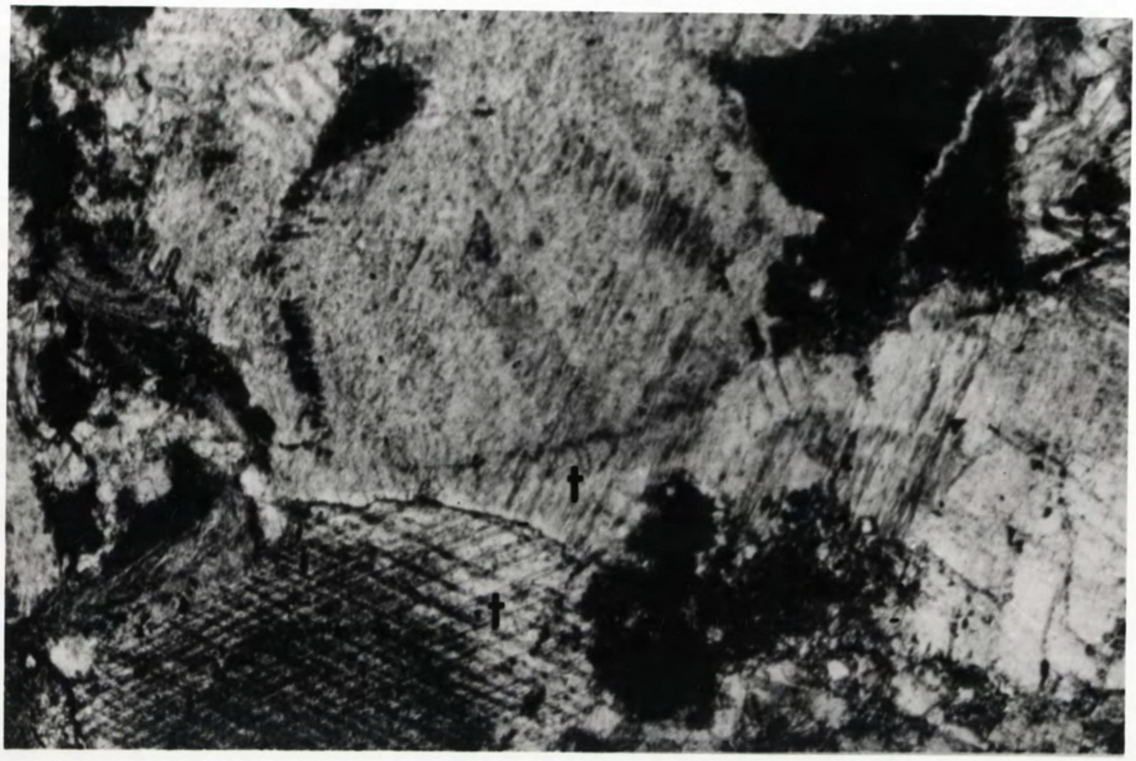


PLATE XX

1: Syntaxial rims (t) from echinoderm debris in contact with each other (X 50).

2: Planar contacts between syntaxial rims (t) and plasma (s) (X 50).


t
t

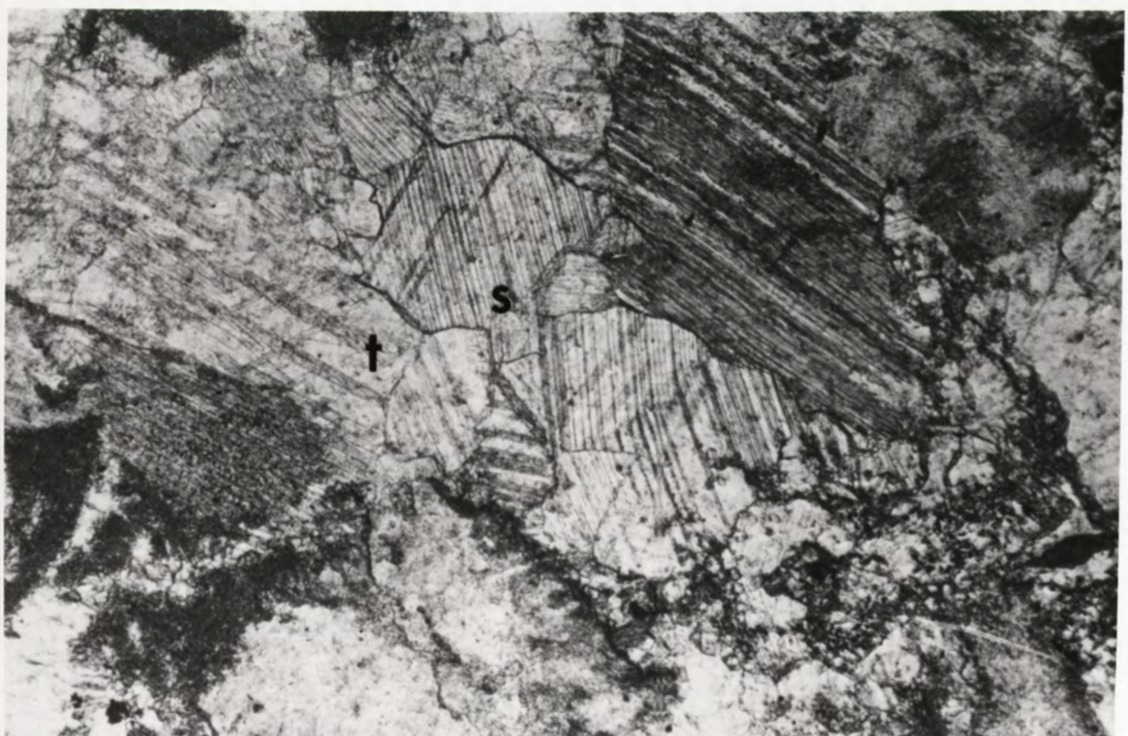

s
t

PLATE XXI

1: Neomorphic syntaxial rim (t) of echinoderm fragment growing across mollusk shell. (Crossed nickols, X 50.)

2: Allochem (t) showing the fibrous habit of encrusting cement (X 50).

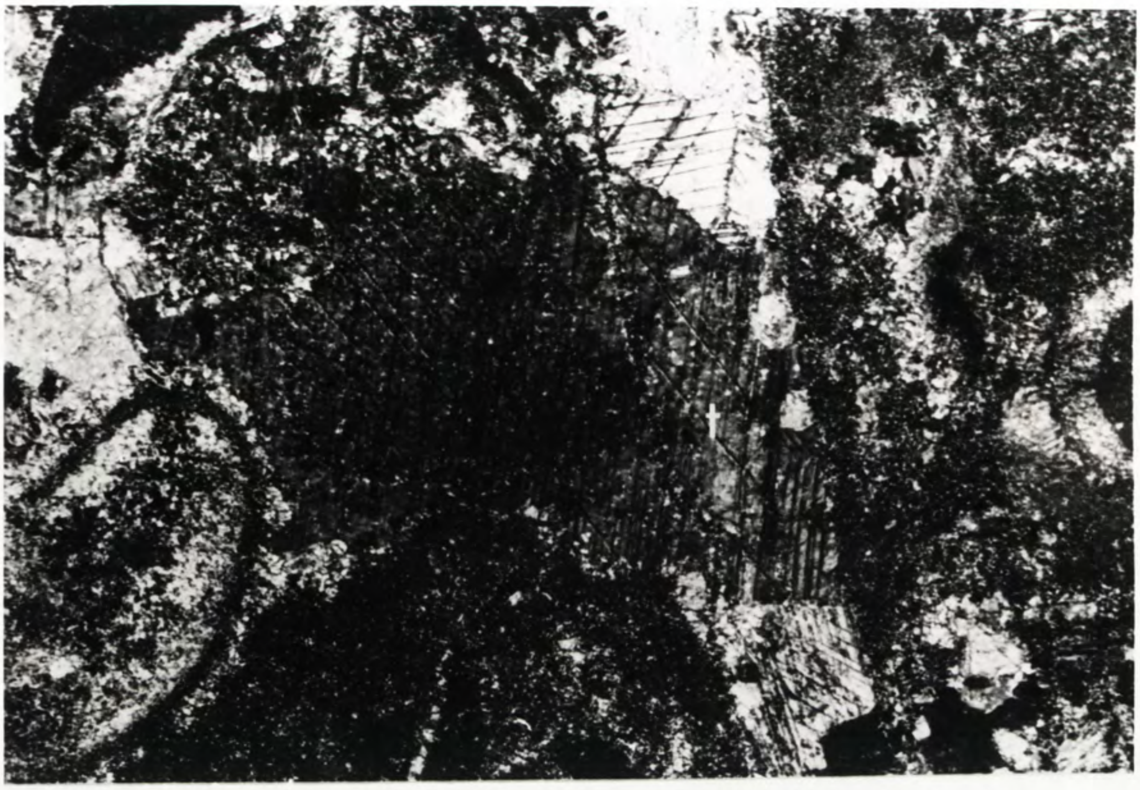


PLATE XXII

1: Allochem showing the lumpyhabit (t) of encrusting cement (X 50).

2: Skeletal grainstone showing the abundance of skeletal debris and coarse nature of the plasma (X 12.5).

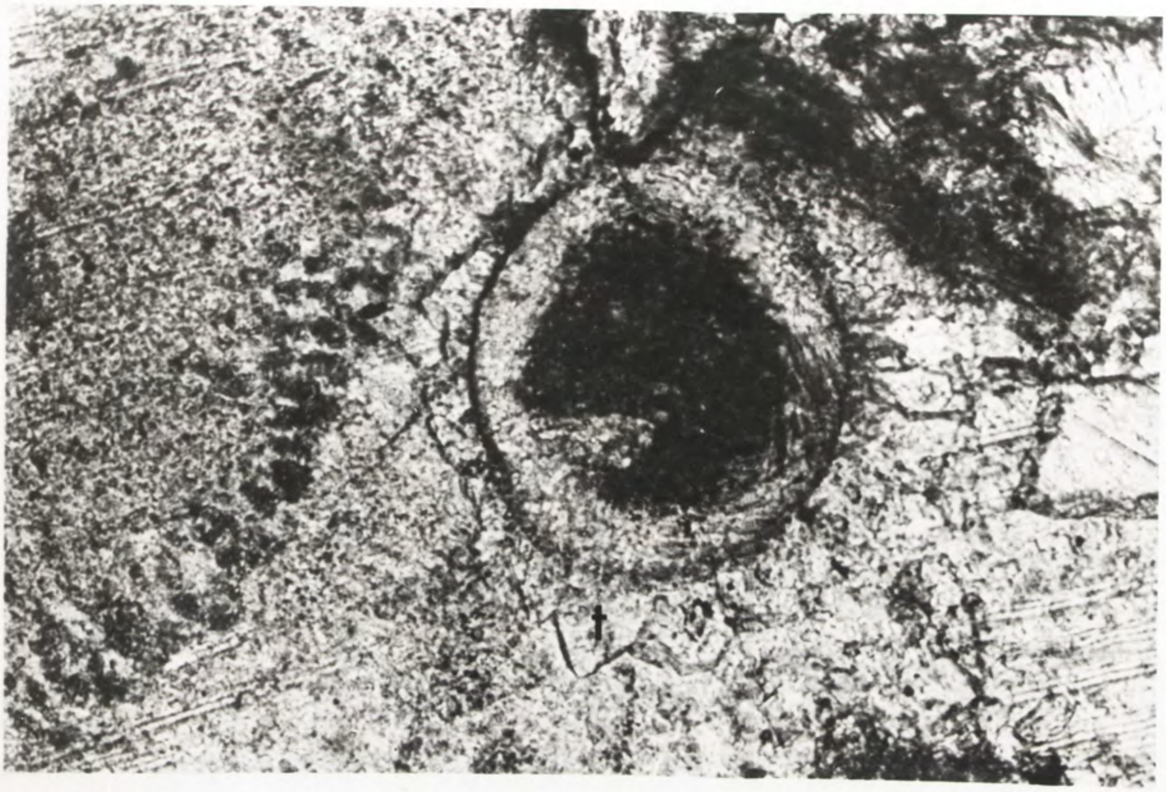


PLATE XXIII

1: Gastropod shell infilled with dense, fine microspar (X 50).

2: Skeletal micritic packstone showing the very fine nature of the plasma and the predominance of echinoderm debris (X 12.5).

PLATE XXIV

1: Complete exposure of the Flaggy Limestone Member at Clear Hill. The observer is standing on the Cavan Limestone/Fifeshire Formation boundary. The prominent outcrop by the pylon is the Bluff Limestone Member.

2: Bluff Limestone Member at Clear Hill.

PLATE XXV

1: Surface of _Cystiphyllum_ biostrome.

2: Base of Yellow Limestone Member (indicated by rule) near Mountain Creek Bridge, marked by massive algal limestone. (Rule is 180cm long.)

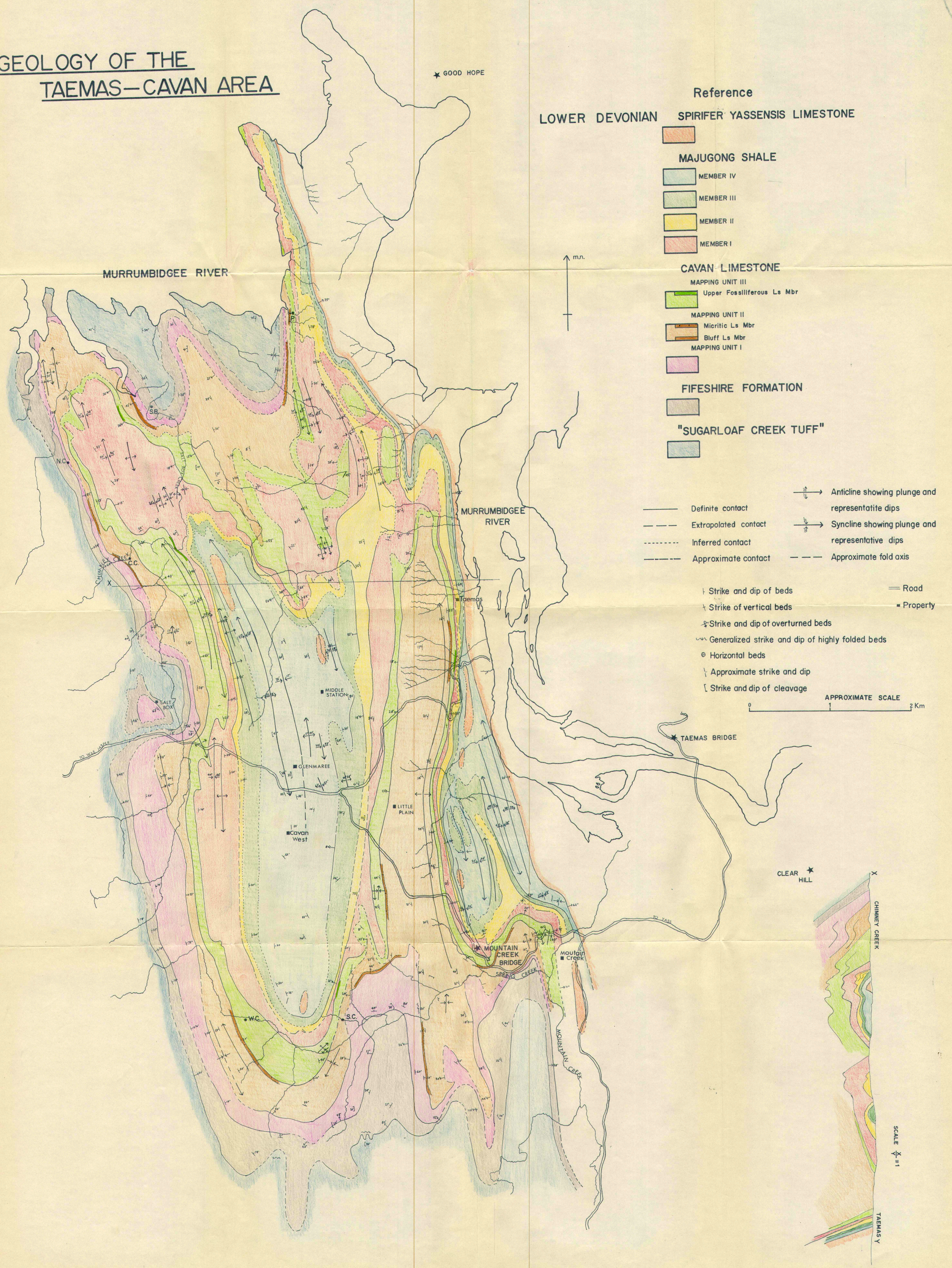
CAVAN LIMESTONE, TAEMAS BRIDGE

CAVAN LIMESTONE, MOUNTAIN CREEK BRIDGE

CAVAN LIMESTONE, CLEAR HILL

CAVAN LIMESTONE, GOOD HOPE

GEOLOGY OF THE TAEMAS—CAVAN AREA



LITHOLOGY	STRUCTURES	BEDDING & PARTING	COLOUR	FOSSILS	REMARKS(abbreviations)	
Skeletal grainstone	Laminations, parallel	b Blocky	Munsell Colour Rock Chart	Fossils in general	abnt	abundant
Skeletal wackestone & packstone	" , slightly disturbed	sl Slabby		Algae	cpct	compact
Skel-algal packstone	" , strongly disturbed	sp Splintery		Brachiopods	dk	dark
Mollask-gastropod wackestone	e.g., 3 = Laminations 3 mm thick	f Flaggy		Corals	dnse	dense
Skeletal micritic wackestone		e.g., b, 7 = Beds 7 cm thick, with blocky parting		Crinoids	fld	feldspar
Micritic mudstone	Graded bedding			Echinoids	fri	friable
Microspar wackestone	Cross bedding			F Favositids	fss	fissile
Pelletal wackestone & packstone	Mudcracks	Bed thickness ≤ 3 cm		Gastropods	hem	hematite
Terrigenous & pelletal wackestone & packstone	Bioturbation	Bed thickness > 3 cm ≤ 30 cm		Lamellibranchs	inter	intercalation
Algal limestone	Styolites	Bed thickness > 30 cm		Ostracods	interlam	interlamination
Gastropod wackestone	Birdseye			Stromatoporoids	intras	intraclasts
Calcrete	Intraclastic			T Tentaculites	lams	laminations
Marl	Pull-aparts			Trilobites	m/	much
Clay			mic	micaeous	slst	siltstone
Shale			micr	microspar	sndy	sandy
Siltstone			mttle	mottle	srtg	sorting
Sandstone			nods	nodules	stky	sticky
No outcrop			rnd	rounding	terr	terrigenous
Very poor outcrop			sbmt	submature	whg	weathering
Interbedded rock types; r(right) & l(left) refer to individual lithologies			sli	slightly	vrf	volcanic rock fragments
Lithologic complex						